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SUBSTITUTION RATES AND ECONOMIC OPTIMA IN CORN-SOYBEAN MEAL RATIONS FOR GROWING-FINISHING SWINE

by

Robert Alan Johnson

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INTRODUCTION

Previous research at the Iowa Agricultural Experiment Station measured the rate and efficiency of gain by growing-finishing swine fed various combinations of corn and soybean meal (Ashton _et al_., 1955; Jensen _et al_., 1955; Speer _et al_., 1956). Production functions derived from these data expressed pounds of gain beyond weaning as a function of pounds of corn and soybean meal consumed beyond weaning. The substitution rates of soybean meal for corn, as well as the quantities of corn and soybean meal required for a specified amount of gain, were derived from these functions. Equation of the substitution rate with the price ratio of the ingredients provided the combination of ingredients which resulted in the minimum cost of the ration (McKee, 1955; Woodworth, 1954; Heady _et al_., 1954c, 1958). Thus, the principle of the "least cost" ration was adapted to specification of economic optima in rations for growing-finishing swine.

The minerals and vitamins added to the rations in these earlier studies were maintained at a constant level throughout the growing-finishing period. It is known that the requirements of the pig for minerals and vitamins, expressed on a per unit of diet basis, decrease as the animal becomes heavier. Therefore, a study was conducted by Johnson (1963) at the Iowa Station to provide mineral and vitamin premixes which would more adequately supply the requirement of the pig for minerals and vitamins at each stage of the growing-finishing period. These mineral and vitamin premixes could then be utilized in the study reported herein involving the least cost ration technique. The study by Johnson (1963) indicated that the total levels of minerals and vitamins in the ration could be markedly reduced from the National Research Council (National Academy of Sciences, 1959) requirements during the 75 to 150 pound and 150 to 200 pound weight periods without significantly affecting rate and efficiency of gain, carcass backfat or metacarpal bone ash content. The minerals and vitamins and the percent by which they were decreased below N. R. C. recommended allowances during the 150 to 200 pound weight period follow: calcium, 46; phosphorus, 11; riboflavin, 15; pantothenic acid, 21; niacin, 36; vitamin B_{12}, 60 percent.

The effect of a change in the components of the ration on carcass quality was not considered in the early research on the least cost ration technique for swine (McKee, 1955; Woodworth, 1954; Heady _et al_., 1954c, 1958). Although the literature is not entirely consistent in this respect, in general a change in protein level in the ration will affect a corresponding change in carcass quality. For example, an increase of two units percent in the crude protein in the ration has resulted in an average increase of one unit percent ham and loin in the carcass at the Iowa Station. Since a change in carcass quality may affect the price received for the pig, the effect of a shift from one least cost ration to another on carcass quality must be considered by the producer. The decision concerning the economic justification of a change in the components of the ration may then be given more accurate consideration.

The effect of a possible carry-over of nutrients from a treatment in an initial weight period on the response in a subsequent weight period is another aspect which was not considered in the previous studies. One basic assumption, underlying the least cost ration technique, is that the response of the pig in a given weight period is independent of the response in a previous period. Thus, this assumption should be tested to determine its validity. Protein and carbohydrates are the nutrients which deserve prime consideration since the least cost ration technique has been based on the use of these components.

With this general background in mind, the following study was initiated to evaluate the least cost ration technique for growing-finishing swine. The research was conducted: first, to determine the substitution rate of soybean meal for corn from production functions fitted to the data and based on a reduction in minerals and vitamins during the growing-finishing period; second, to determine the effect of a change in the components of the ration on carcass quality; third, to test the assumption, underlying the least cost ration technique, that the response of the pig in a given weight period exerts a negligible effect on the response in subsequent weight periods.

REVIEW OF LITERATURE

Protein Level Studies

Effect on performance

Early trials   Early experimental attempts to elucidate the protein requirement of the growing-finishing pig, nearly three decades ago, indicated a requirement higher than the levels currently regarded as optimum for maximum performance. The approximate protein levels suggested were 18 to 20 percent for pigs from 50 to 75 pounds, 15 to 17 percent from 75 to 150 pounds and 12 to 14 percent from 150 to 200 pounds in dry lot (Mitchell, 1939; Carroll and Burroughs, 1939; Crampton and Ashton, 1942, 1946). However, rations formulated in early work did not necessarily contain adequate amounts of water soluble vitamins, unless more than adequate amounts of protein were fed. Furthermore, the advent of antibiotics possibly altered the requirement for protein.

Thus, the early 1950's were marked by a re-evaluation of the protein requirement of the pig. Cunha *et al.* (1950) suggested that the protein requirement of the growing pig needed reexamination, using adequate amounts of vitamin B_{12}. Catron *et al.* (1952) reported that the addition of an antibiotic to rations with protein levels of 14 percent from 35 to 75 pounds of body weight, 11 percent from 75 to 150 pounds and 8 percent from 150 to 200 pounds resulted in performance equal to that of rations with 6 percentage units more of protein. Catron *et al.* (1952) further stated that, contrary to previous recommendations, higher levels of protein were in excess of the pig's requirements. The protein levels found to be adequate for maximum performance in these trials were confirmed by other workers (Robison, 1952; Meade, 1956; Hanson *et al.*, 1955).

Nevertheless, other studies (Burnside *et al.*, 1954; Hoefer *et al.*, 1952; Wallace *et al.*, 1954) indicated that performance was improved by protein levels approximately 2 percentage units higher than the aforementioned levels. Wahlstrom (1954) found that a 12 percent protein level produced slower gains than 14 to 18 percent protein levels for pigs from 40 to 100 pounds and a 9 percent protein ration did not support normal growth of pigs from 100 to 200 pounds of body weight.

Whereas the previously mentioned trials involved systematic decreases in protein levels at each stage of the growing-finishing period, many workers followed a different approach. In these tests, protein levels remained unchanged throughout the stages of growth and finish, Jensen (1953) noted maximum rate and efficiency of gain on a 16 percent corn-soybean meal ration when testing levels of 8, 12, 16 and 20 percent protein. Four trials conducted by Becker *et al.* (1954) in order to evaluate protein levels of 8 to 18 percent, indicated that pigs required a minimum of 14 percent protein from 40 to 100 pounds and a minimum of 12 percent protein from 100 to 200 pounds on corn-soybean meal rations. The addition of an antibiotic to corn-soybean meal rations produced maximum average daily gain at a protein level of 14 percent in a study conducted by Jensen et al. (1955) to evaluate protein levels of 10, 12, 14, 16, 18 and 20 percent.

Speer et al. (1956) compared corn-soybean meal rations with protein levels of 8, 10, 12, 14, 16 and 18 percent in two trials conducted on pasture. Maximum rate and efficiency of gain were attained at 16 percent protein from 30 to 75 pounds and at 14 percent protein from 30 to 200 pounds of body weight. Evaluation of protein levels of 8 to 18 percent by Lassiter et al. (1955) resulted in the following minimum protein levels recommended for maximum growth: 14 to 16 percent for pigs from 30 to 100 pounds in dry lot and 12 to 14 percent for pigs from 30 to 200 pounds in dry lot and on pasture. Maximum rate and efficiency of gain from weaning to 200 pounds of weight were noted at 12 percent protein by Becker et al. (1955), when comparing protein levels of 8, 10, 12, 14 and 16 percent on pasture. They found that protein levels above 8 percent for pigs from 100 to 200 pounds did not improve performance.

The studies of Speer et al. (1956), Jensen et al. (1955), Lassiter et al. (1955) and Becker et al. (1955) indicated that satisfactory performance could be attained by pigs consuming a 10 percent protein ration either in dry lot or on pasture.

Recent trials More recent studies on the effect of protein level on performance have not resulted in complete agreement. Some workers have shown improved rate and efficiency of gain on protein levels 2 to 3 percentage units higher than those previously recommended. Beacom (1959a) examined protein levels of 13, 15, 17 and 19 percent from 35 to 70 pounds; 12, 13.5, 14.5 and 15.5 percent from 70 to 130 pounds; and 11, 12, 12.5 and 13 percent from 130 to 200 pounds of body weight respectively and found that feed efficiency was not significantly affected. Although the higher levels of protein increased average daily gain for the entire period, the effect was inconsistent among the stages. Seymour *et al*. (1964) found that corn-soybean meal rations consisting of 17 percent protein from seven weeks of age to 125 pounds of body weight and 14 percent from 125 to 200 pounds were superior to rations containing 4 percentage units less protein. Protein levels of 17 percent to 100 pounds and 15 percent thereafter resulted in significantly more rapid and efficient gains than 4 percentage units less protein, as noted by Wallace *et al*. (1963). Baird *et al*. (1962) found more rapid and efficient gains at protein levels of 15 percent from weaning to 125 pounds of body weight and 12 percent from 125 pounds to market weight, than at protein levels of 12 and 9 percent in those weight ranges.

Rations containing 18, 16 and 14 percent protein from 40 to 125 pounds body weight and then reduced to 15, 11 and 11 percent protein from 125 to 200 pounds were examined by Aunan et al. (1961). Although the initial protein levels had no significant effect on gain, a significant decrease in gain resulted when a 12 percent protein ration fed throughout was compared to the low and medium protein levels.

Much of the recent work, as was true of the early work, has involved the comparison of protein levels remaining unchanged throughout the growing-finishing period. The bulk of the work has been concerned with corn-soybean meal rations. All of the studies have shown adequate response at protein levels lower than those cited previously. Neither Becker et al. (1962) nor Kropf et al. (1959) noted any difference in response to protein levels of 12 and 16 percent fed throughout the growing-finishing period. Noland and Scott (1960) compared corn-soybean meal rations containing 12, 16 and 20 percent protein. Although they noted a significant linear regression of average daily gain on protein levels for pigs from 40 to 75 pounds, there was no difference in response to the protein levels for the remaining stages of the growing-finishing period. Rate and efficiency of gain were not improved by corn-soybean meal diets of 14 and 16 percent protein when compared to a corn-soybean meal diet of 12 percent protein fed by Dukelow et al. (1963) to pigs from 55 to 200 pounds of body weight.

Corn-soybean meal diets containing 10, 11, 12, 13, 14, 15, 16, 17 and 18 percent protein were investigated by Clawson et al.

(1962) in an intensive study of energy-protein ratios. They asserted that pigs fed on the lower protein levels (10, 11, 12 percent) made satisfactory growth and that there were no marked differences in response to levels of protein.

Reimer and Meade (1964) found in one trial that 14 percent protein fed throughout the growing-finishing period supported as rapid and as efficient gains as 16 percent protein to 100 pounds of body weight and as 13 percent from 100 pounds to the remainder of the 88 day period. Rations containing 12 and 13 percent protein fed throughout the growing-finishing period supported as rapid and as efficient gains as 14 and 15 percent protein to 100 pounds of body weight and 11 and 12 percent protein for the remainder of the 88 day period in a second trial by Reimer and Meade (1964).

Wagner et al. (1963) noted that, as the protein level was increased from 13 to 19 and 25 percent, rate and efficiency of gain were reduced. Hays et al. (1963) found that pigs fed 18 percent protein gained significantly slower than pigs fed either 12 or 15 percent protein. However, they suggested that improved gain at the 15 percent protein level indicated that the 12 percent protein ration was a borderline level for growth.

A preponderance of literature thus indicates that levels of 10 to 20 percent protein in rations fed to pigs in dry lot are adequate for satisfactory performance, although rate and efficiency of gain are improved as the protein level is increased from 10 to 18 percent.

Effect on carcass quality

Early trials   Early research on the effect of protein levels on carcass quality did not show agreement among workers. Crampton and Ashton (1946) stated that reduction of the protein level from 15 to 13 percent did not affect carcass excellence. Catron et al. (1952) reported that the reduction of 6 percentage units from 20, 17 and 14 percent protein at 35 to 75, 75 to 150 and 150 to 200 pounds body weight, respectively, resulted in no significant differences in backfat, percent lean cuts or dressing percent.

However, Robison et al. (1952) noted a consistent increase in percent lean cuts as the protein level in the ration was increased from 10 to 20 percent. Wilson et al. (1953) fed groups of pigs protein levels of 14, 17 and 20 percent from 50 to 75 pounds; 11, 13 and 16 percent from 75 to 150 pounds; and 9.5, 10 and 12 percent from 150 to 210 pounds. They found increased percent lean cuts from feeding the higher protein levels. Protein levels of 14, 16 and 18 percent for pigs from 40 to 130 pounds and 10, 12 and 14 percent from 130 to 200 pounds produced significantly leaner carcasses than protein levels of 12 and 9 percent for those weight ranges (Wahlstrom, 1954). Wallace et al. (1954) discovered that dressing percent was significantly higher in those pigs receiving 14.3 percent protein than in those receiving either 17.6 or 20.9 percent protein. Feeding pigs protein levels from 10 to 20 percent by Ashton et al. (1955) resulted in a significant increase in percent lean cuts (about 2 percentage units) as the level of protein was increased.

Recent trials Many recent studies (Bowland et al., 1961; Stevenson et al., 1960; Beacom, 1959b; Seymour et al., 1964; Wallace et al., 1963) have shown that increasing the protein level above N. R. C. (National Academy of Sciences, 1959) recommendations during the three stages of the growing-finishing period will increase carcass characteristics such as percent lean cuts and rib eye area. Wallace et al. (1963) noted significantly higher dressing percent on 13 percent protein for pigs to 100 pounds of body weight and 11 percent thereafter than for rations containing 4 percentage units more protein at each stage. Other reports of similar treatment of protein levels (Aunan et al., 1961; Becker et al., 1962) have not shown an increase in the percent of lean cuts in the carcass.

Many of the recent reports on carcass quality are correlative with those reports previously discussed concerning the effect of protein level on performance. Therefore, they will be concerned with the investigation of protein levels which remain unchanged throughout the growing-finishing period.

Again, some disagreement exists concerning the effect of increasing protein levels on carcass quality. Dukelow et al. (1963) found no significant difference in backfat, loin eye area or percent ham and loin in pigs receiving protein levels of 12, 14 and 16 percent. When comparing the averages of 10, 11 and 12 percent protein rations; 13, 14 and 15 percent protein rations; and 16, 17 and 18 percent protein rations, Clawson et al. (1962) noted no significant differences in lean cuts, loin eye area or backfat.

However, other studies have shown a marked response in carcass quality due to protein level. Becker et al. (1962) and Kropf et al. (1959) showed that a protein level of 16 percent resulted in decreased dressing percent, decreased backfat, increased loin eye area and increased percent lean cuts when compared with a protein level of 12 percent fed to pigs throughout the growing-finishing period. Corn-soybean meal rations with protein levels of 12, 16 and 20 percent protein were fed by Noland and Scott (1960). They found that the 16 and 20 percent protein rations produced longer carcasses with a greater yield of primal cuts than did the 12 percent protein rations.

In three other studies (Wagner et al., 1963; Seerley et al., 1964; Hays et al., 1963), backfat and dressing percent decreased and percent lean cuts increased as the protein level was increased above 12 to 13 percent for growing-finishing pigs.

In general, increasing the protein level above 10 percent of the ration fed throughout the growing-finishing period has resulted in increases in percent lean cuts and loin eye area and decreases in backfat and dressing percent. Increasing the protein level above N. R. C. recommendations for each stage of the growing-finishing period has not consistently produced similar results in carcass quality.

Least Cost Rations and Linear Programming

Least cost rations for swine

Previous investigations at the Iowa Station measured the rate and efficiency of gain by growing-finishing swine fed various combinations of corn and soybean meal (Ashton et al., 1955; Jensen et al., 1955; Speer et al., 1956). Production functions derived from these data expressed pounds of gain beyond weaning as a function of pounds of corn and soybean meal consumed beyond weaning. The substitution rates of soybean meal (high protein source) for corn (energy source) were then determined from these functions. Equating the substitution rate with the price ratio of the ingredients provided the combination of ingredients which resulted in the minimum cost of the ingredients per unit of gain (McKee, 1955; Woodworth, 1954; Heady et al., 1954a, 1954b, 1954c, 1958).

Other energy and protein sources may replace corn and soybean meal at their relative substitution values if their prices warrant doing so to achieve the most economical mixture. However, this is based on the assumption that the comparative value of these sources would be known from the results of biological tests. If not, it must be assumed that they are equal in value to corn or soybean meal.

It was determined in the previously mentioned studies that soybean meal substitutes for corn in the ration at a decreasing rate as the protein percentage increases in the ration at a constant body weight of the pig and also as the pig matures to a heavier body weight. This property of the changing value of soybean meal relative to the value of corn provides the basis for changing the mixture of the ration as these ingredients change in price.

The effect of the variation of percent protein in the ration on time required by the pig to attain market weight in dry lot was also investigated (Heady et al., 1954c; Woodworth, 1954). They noted that approximately 30 more days were required to produce 191 pounds of gain with a 10 percent protein ration when compared with 12 and 20 percent protein rations. Ten more days were required by the 12 and 20 percent protein rations when compared with 14, 16 and 18 percent protein rations. Production functions representing time between weaning and market weight as a function of pounds of corn and soybean meal consumed between weaning and market weight were used to predict the values. The pasture data (McKee, 1955; Heady et al., 1958) indicated that the 10 percent protein ration only required about 14 more days between weaning and market weight when compared with 12, 14, 16 and 18 percent protein rations.

The Iowa Station (1954, 1955) conducted two experiments designed to evaluate least cost rations and compare them to least time and free-choice rations for growing-finishing pigs on pasture and in dry lot. The least cost mixture was based on the prices of corn and a 35 percent protein supplement and the weight of the pigs. They found that the least cost ration was more economical than the free-choice ration in dry lot, but that on pasture the least cost ration was less economical than the free-choice ration due to grinding costs. Comparison of the least cost ration with the least time ration indicated that the least cost ration was cheaper on pasture but more expensive in dry lot.

It should be explained, however, that the 35 percent protein supplement contained other protein ingredients in addition to soybean meal and that the levels of minerals and vitamins contained in the supplement were varied correspondent with the variation in the level of the supplement due to changes in prices. Therefore, the levels of minerals and vitamins in the ration may have been either less than or in excess of the nutrient requirements as the pigs became heavier. Similarly, the cost of the other protein ingredients may have been excessively higher than that of soybean meal, all of which could have caused less efficient gains and excessive costs.

Least cost rations for other species

Broilers and turkeys Balloun and Heady (1956) and Balloun *et al.* (1957) conducted research to measure the effectiveness of the least cost ration technique for broilers and turkeys. Production functions derived from these data represented the gain of the bird over the production period as a function of pounds of corn and soybean meal consumed over the period (Heady *et al.*, 1956a, 1956b). Again, substitution rates of soybean meal for corn were derived from the production functions and the least cost ration was predicted.

Optimum marketing weights based on the marginal productivity of feed and the feed bird price ratio were also derived to predict the most profitable marketing weights consistent with minimum feed costs. Furthermore, the time required for the broiler to attain marketing weight was predicted from regression functions relating time to pounds of corn and soybean meal consumed over the production period. Comparison of the least cost with the least time rations indicated that they were not identical under normal price relationships.

Balloun *et al.* (1957) found that, from a practical standpoint, savings realized during the first six weeks with least cost rations for turkeys were small, but became quite substantial during the remaining phases of the growing-finishing period. The least cost rations resulted in satisfactory performance for both broilers and turkeys and contributed towards savings in feed costs.

Dairy cows   Heady et al. (1956c) investigated the possibility of applying the least cost ration technique to dairy cows. Production functions which represented milk output as a function of pounds of hay and grain consumed, cow production ability and time period involved were derived (Heady et al., 1956d). Substitution rates of forage for grain in producing specified quantities of milk were also predicted. Therefore, depending on the relative prices of milk, grain and hay at various time periods, the optimum least cost ration for a particular price of milk can be calculated.

A more comprehensive study concerning the application of the least cost ration technique to the milk output of dairy cows was recently undertaken by Heady et al. (1964a, 1964b). Milk production functions which represent milk output as a function of weekly hay and grain consumption, stage of lactation, cow production ability, index of inbreeding, body weight, age of cow, index of cow maturity and environmental temperature were derived. Substitution rates of one variable for another and profit maximizing levels of the various variables were also predicted. Several production conditions may be approximated from the production functions by fixing the variables at specified levels and calculating the milk output. Therefore, many aspects of dairy cow nutrition, breeding, and management may be included in a single production function. However, some question concerning the interpretation of the data may arise from consideration of such a complex function.

Beef cattle Production functions have also been applied to beef production by Heady et al. (1961). The functions express the relationship between pounds of gain over the production period and pounds of corn, linseed meal and forage consumed over the production period. Rates of substitution of linseed meal for corn and forage for corn were derived from the functions to specify the optimum economical mixture of the ration.

However, one limitation of these data which must be considered is the fact that the observations on which these functions were based were taken under conditions which are no longer applicable. The majority of beef cattle are now fed high concentrate rations in dry lot. The rations also contain feed additives which were developed since the time when the observations, on which these functions are based, were taken.

Linear programming

Least cost rations have been developed rather readily when working with just two variables (e.g., corn and soybean meal), while keeping all others constant. However, as more and more ingredients are introduced as variables into the ration, the calculation of various quantities and the interpretation of concepts become extremely complicated. The linear programming technique employed on the electronic computer may become a valuable tool for specifying economic optima in swine rations as these complex situations arise. However, certain limitations concerning the application of linear programming to the prediction of least cost rations must be considered. These limitations are discussed at a later point in this section.

The application of linear programming to the mixing of feeds was initially discussed by Waugh (1951) in reference to a minimum cost dairy feed. Coincident with this paper was the discussion of Christensen and Mighell (1951) concerning the relationship between food production strategy and the protein-feed balance. They represented the minimum cost of a ration containing corn and protein by a convergence of lines, denoting protein and total digestible nutrients, on a simple graph. Recent excellent discussions of the application of the techniques of linear programming to the formulation of feeds may be found in Potter *et al*. (1962) and Heady and Candler (1958).

Swine Bowland (1962a, 1962d) designed a test in which electronically computed rations were used to evaluate N. R. C. nutrient requirements for growing-finishing swine. He found improved rate and efficiency of gain during the growing period from a ration containing a 15 percent safety margin of protein, lysine, methionine, calcium, phosphorus, riboflavin, pantothenic acid, and vitamins A and D when compared with a linear programmed ration designed to meet nutrient requirements.

Rate and efficiency of gain during the finishing period were improved by a ration containing corresponding increases of protein, lysine and methionine when compared with the linear programmed ration designed to meet nutrient requirements. No effect of carcass quality was noted.

After testing the N. R. C. nutrient requirements for growing-finishing swine by linear programmed rations, Bell (1961) concluded that lysine, tryptophan or protein levels, rather than minerals or vitamins, were among the factors limiting growth. In a later report, Bell (1963) confirmed that rations with the augmented nutrient levels were superior in the growing period and that the failure of minimum standard rations appeared to be due to deficient levels of protein, lysine or methionine. Results favored the higher protein level during the finishing period but were not significant.

The N. R. C. feeding standard was subjected by Bowland (1962b) to a biological test designed to determine whether the nutrients were stated in terms of optimum requirements. Since feed intake and rate and efficiency of gain varied in three to nine week pigs on linear programmed rations, he concluded that restrictions other than meeting nutrient requirements must be used. In the same study, two low cost linear programmed starter rations resulted in rate and efficiency of gain equal to the standard control and one of the computed rations resulted in a cheaper cost of gain.

Other workers have experienced some problem with reduced feed intake of linear programmed rations. Crampton et al. (1960) compared a nutritionally proven control ration to an electronically computed least cost ration fed to pigs weaned at 10 pounds. They found that while gains were about equal, the computed ration resulted in an 11 percent improvement in feed efficiency and was $26 per ton cheaper than the control ration. Crampton et al. (1960) credited the improvement to an improved balance of nutrients and to a reduction of nutrient excesses. However, pigs on the computed ration ate significantly less feed than the pigs on the control ration. Thus, Lloyd et al. (1962) compared this nutritionally proven ration to three computed rations designed to increase nutrient intake. The computed rations were based on added iodinated casein, an increased variety of feed ingredients and an increased concentration of leucine, riboflavin, pantothenic acid, and vitamins A and D. While cost of each of the computed rations was less than that of the control ration, greater feed intake and average daily gain were noted on the control ration. Thus, the defect in the computed rations centered on sub-optimal feed intake. Costain et al. (1962) then attempted to compare this same nutritionally proven control ration to two of the computed rations modified for palatability and/or texture. The computed rations which were modified by the addition of molasses, skim milk and sucrose were consumed in greater quantities but still not in quantities equal to that of the control ration. They concluded that factors other than acceptability were involved in optimal intake.

Other species   Linear programming procedures were used by Church et al. (1963) to formulate fattening rations for weaner calves using either digestible energy or estimated net energy, crude protein, crude fiber, calcium and phosphorus as the basis for formulation. Chemical analysis of the computed rations indicated reasonable agreement between specifications and the analysis for crude protein, crude fiber and phosphorus.

Maddy et al. (1963), using linear programming, calculated sample broiler starter diets based on trials conducted to test the validity of the assumptions used for nutrient requirements, specifically that of availability of amino acids. Thus, the amino acid values were adjusted for biological availability although other minimum and maximum nutrient levels were not biologically tested.

A linear programmed least cost ration for chicks was designated by Arscott and Brown (1961) as "not the most economical" because of poor results in performance caused by a deficiency of lysine in cottonseed meal. They emphasized that one would need a biological test of linear programmed least cost rations until more information is available on nutrient requirements and feedstuffs limitations--particularly when the ration deviates considerably from normal feedstuffs.

Potter et al. (1962) found that a linear programmed least cost diet, formulated to be equal to or greater in nutrient content than a New England College Conference broiler ration, produced equal body weight and improved feed efficiency when fed to chicks.

Limitations Certain limitations, as was previously mentioned, should be considered with regard to linear programmed, electronically computed least cost rations. Most of the previously mentioned research reports based calculations on present requirements of various species for various nutrients. These requirements were derived by keeping nutrients, other than the one being tested, at a constant level in the ration. Thus, the requirements may or may not be correct based on the effect of nutrient excesses, imbalances and/or interactions.

Bowland (1962c, 1963) recently stated that the ideal in linear programming is to formulate rations which meet nutrient requirements of a completely balanced ration; that this ideal assumes that nutrient requirements are known in detail and are not subject to alteration by interactions associated with nutrient combinations and other variables; and that this latter assumption is not true.

The studies by Arscott and Brown (1961), Crampton et al. (1960), Bell (1961, 1963) and Bowland (1962a, 1962b, 1962d) which were undertaken to test the adequacy of a recognized feeding standard point to the need to develop accurate biological measures of the many ingredients used in linear programmed rations. The biological value of nutrients may initially be derived by animal experimentation; or, as Crampton (1962) has pointed out, it has now become feasible to biologically test the status of feeding standard descriptions of rations and to examine in some systematic way the consequences of modifications in nutrient levels. Biological tests must be employed in some manner before effective use may be made of least cost rations linear programmed on the electronic computer or formulated in any similarly rigorous manner.

EXPERIMENTAL

General Objectives

These experiments were conducted: first, to determine the substitution rate of soybean meal for corn from production functions fitted to the data derived from feeding rations in which minerals and vitamins were reduced commensurate with increasing weight of the pig; second, to determine the effect of a change in the components of the ration on carcass quality; third, to test the assumption, underlying the least cost ration technique, that the response of the pig in a given weight period exerts a negligible effect on the response in subsequent weight periods.

General Experimental Methods

The three experiments which comprise this study are on file in the Swine Nutrition Section of the Animal Science Department, Iowa State University, Ames, Iowa. These experiments are under the title of Swine Nutrition Experiments 6323, 6335 and 6417. Many of the procedures and materials were common for the experiments and will be discussed in general at this point.

All of the pigs were obtained from the swine nutrition farm breeding herd and were crossbreds. Within 24 hours after birth each pig was weighed, ear notched and given an iron treatment for the prevention of anemia. Male pigs were castrated at approximately five days of age. All pigs were weaned at approximately two weeks of age and received injections of modified hog cholera virus and antiserum at seven weeks of age.

Most of the pigs were selected for experimental baby pig nutrition studies for an approximate period of four weeks prior to being selected for the experiments reported herein. After receiving an 18 percent pig starter ration for a week, the pigs were then randomly allotted from littermate outcome groups to a randomized complete block design of experimental treatments. The pigs remained on experiment until they reached an approximate body weight of 205 pounds.

The pigs were housed on concrete in outside pens containing an opening to the south. Pens were thoroughly cleaned before the initiation of each experiment and then cleaned daily during the course of the experiment.

Water was provided by automatic float controlled waterers during the summer and in pans twice or three times daily, as needed, during the winter. The pigs had free access to feed provided in self feeders.

Animals which died during the course of the experiments were taken to the Iowa State University Veterinary Diagnostic Laboratory for examination. The gain for the remaining pigs in the pen was used in calculation of average daily gain for that pen. Feed required per pound of gain was adjusted by subtracting the estimated feed consumed by the particular pig from the total feed consumed to that date. The assumption was made that the feed efficiency for the pig removed was the same as that of the pigs remaining in the pen.

When the pigs attained an approximate body weight of 205 pounds they were weighed, tattooed, and shipped to the Geo. A. Hormel and Co. packing plant at Fort Dodge, Iowa, for the collection of carcass data. The pigs were slaughtered the following day at which time the heads and leaf fat were removed. The carcasses hung in the cooler (approximately 36 degrees F.) for 24 hours after which the chilled carcass weight was recorded just prior to cutting.

Carcass backfat was the average of three measurements taken at the first rib, last rib, and last lumbar vertebra, measured to the nearest five-hundredths of an inch. This measurement was corrected to a 200 pound live weight basis using correction factors suggested by Durham and Zeller (1955). The percentage of ham and loin was determined by dividing the sum of the trimmed hams and trimmed loins by the chilled carcass weight and converting to a percentage basis.

All of the data collected in each of the three experiments were statistically analyzed according to methods described by Snedecor (1956). Four pigs were included in each pen which was considered the experimental unit in all of the experiments.

Observations were taken on the amount of body weight gain and the consumption of feed over two week intervals from the beginning of the experiment until the first pig in each replication was marketed in Experiments 6323 and 6335. Final observations on gain and feed consumption were taken when all of the pigs in each pen had been marketed. A series of accumulative summations of gain and corn and soybean meal consumption for each pen of pigs for the entire experimental period was obtained by progressively totaling the interval observations. The production functions representing gain as a function of the consumption of corn and soybean meal were then fitted to all of the series of observations by means of regression analysis.

The problem of autocorrelation is inherent in the process of fitting the functions to the accumulative series of observations on gain, and corn and soybean meal consumption. In other words, each observation used in the fitting of the production function includes all of the previous observations taken on that same pen of pigs. While a series of observations taken on the same pen of pigs exhibits autocorrelation, it is at the same time independent of the series of observations taken on the other pens. Thus, the extent of autocorrelation over the entire series of observations in the study is reduced.

Autocorrelation does not affect the relationship between the independent and dependent variables but causes a problem in making tests of significance by reducing the number of effective observations used in fitting the function. The effective number of observations used in entering tables for tests of significance is less than if autocorrelation were not present.

However, the problem of autocorrelation may be resolved by basing significance tests on the minimum number of effective observations to which the series would be reduced by autocorrelation (McKee, 1955). In this case, the minimum number of effective observations may be regarded as the number of pens of pigs from which observations were taken since independency exists among pens of pigs. The null hypothesis may then be rejected if the tests of the coefficients are significant on the basis of the minimum number of effective observations. However, other alterations in testing must be followed if the tests are not significant. The coefficients in the functions which are reported herein were significant at an acceptable probability level, based on the minimum number of effective observations (30 pens of pigs). Therefore, the problem of autocorrelation was resolved. Autocorrelation was not present in any of the other analyses in these studies.

Quantities of corn and soybean meal required by the pig to attain specified gain contours (equal quantities of gain) were predicted from the production functions. Marginal rates of substitution of soybean meal for corn at the gain contours were derived from these functions. Derivation of the substitution rates was accomplished by substituting the corn and soybean meal quantities into the ratio of the partial derivatives (with respect to corn and soybean meal) of the functions. Gain contours of 15, 35, 55, 75, 100, 125 and 155 pounds of gain beyond 50 pounds initial body weight were chosen in order to represent the amount of gain which might be expected at two week intervals during the production period. Quantities of corn and soybean meal required over gain intervals (between gain contours) were obtained by calculating the difference in the quantities derived at each gain contour. Substitution rates of soybean meal for corn over gain intervals were then calculated using the formula described by Woodworth (1954).

The total amounts of gain resulting from 50 pound increments of feed inputs were also derived from the production functions for rations containing 10 to 20 percent protein. Marginal feed productivities (added gain per pound of added feed) were calculated for the incremental feed inputs for various protein percentage rations by division of the marginal gain by each 50 pound feed input. Similarly, marginal feed productivities over gain intervals were calculated by division of quantities of gain by the quantities of feed required over the intervals.

Functions representing the relationship between the percent ham and loin of the pig at market weight and the total pounds of corn and soybean meal consumed over the production period were also fitted to the data using regression analysis. Autocorrelation did not present a problem in this case, since interval observations were not taken. The change in percent ham and loin affected by a change in percent protein of the ration was then calculated from the data provided by the functions.

In addition, functions expressing the marginal (added) time required to produce a marginal (added) pound of gain were fitted to the observations using regression analysis. Marginal days per pound of gain were calculated as a function of the percent protein in the ration and the marginal quantity of gain over each two week interval. The number of days required to produce a given amount of gain over the gain intervals was calculated by multiplication of the marginal days per pound of gain by the amounts of gain for each gain interval. Addition of the number of days required over each gain interval produced the number of days required to attain a given amount of gain at each gain contour.

The National Research Council (National Academy of Sciences, 1959) recommended nutrient allowances for growing-finishing swine, which was used as a basis for comparison with the nutrient levels provided by the experimental ration treatments, may be found in Table 1. Table 2 illustrates the mineral and vitamin premixes used as a basis for reduction of the mineral and vitamin levels in the experimental rations. The premixes are listed in the total amounts which might normally be added per ton of growing-finishing ration. The added levels of minerals and vitamins were decreased in half when the pigs in each pen attained an average body weight of approximately 110 pounds. The reduction of mineral and vitamin levels was based on the results of a previous study (Johnson, 1963) conducted to provide adequate mineral and vitamin levels for the study reported herein.

The composition and calculated analysis of the various ration treatments are listed in Tables 4 through 9. The ration treatments were formulated by using various combinations of corn and soybean meal to produce the desired protein level.

Protein Level Studies

Experiment 6323 - effect of protein level on performance and carcass quality

Objective The purpose of this experiment was to provide observations on performance and carcass quality to be utilized in the calculation of least cost corn-soybean meal rations for growing-finishing swine.

Procedure This experiment was conducted between April and September 1963. The protein levels of 10, 12, 14, 16, 18 and 20 percent were maintained at a constant level throughout the duration of the experiment.

One hundred and twenty pigs averaging 50 pounds body weight were randomly allotted from litters within initial weight groups with the restriction that sex was balanced over experimental units within replicates. The ration treatments were then replicated five times.

Carcass data were collected after the pigs were slaughtered at a body weight of 205 pounds.

Results and discussion   Summaries of average daily gain and feed required per pound of gain are shown in Tables 10 and 11, respectively and in Figure 1. Percent ham and loin and carcass backfat, yield length and grade are summarized in Tables 12 and 13. Figure 2 illustrates the treatment means for percent ham and loin and carcass backfat. The analysis of variance plan and observed mean squares for all of the criteria are contained in Tables 14 and 15.

There were significant linear and quadratic regressions of average daily gain on protein level for the 50 to 110 pound period with the maximum gain occurring at the 16 and 20 percent protein levels. Significant linear, quadratic and cubic regressions of average daily gain on protein level existed during the 110 to 205 pound interval and for the entire period with maximum gain at the 14 and 16 percent protein levels, respectively. Adequate response was obtained at the lowest level of protein where the daily gain averaged 1.21 pounds for the entire period. These results agree favorably with the results of Jensen et al. (1955) who found a response of 1.30 pounds of average daily gain over the entire period at the same protein level. They also noted maximum gain at the 16 percent protein level for the entire period.

Significant linear, quadratic and cubic regressions of feed required per pound of gain on protein level were determined for each stage of the growing-finishing period, as well as for the entire period. Maximum feed efficiency was noted

Figure 1. Experiment 6323 - effect of protein level on average daily gain and feed required per pound of gain for the entire experimental period

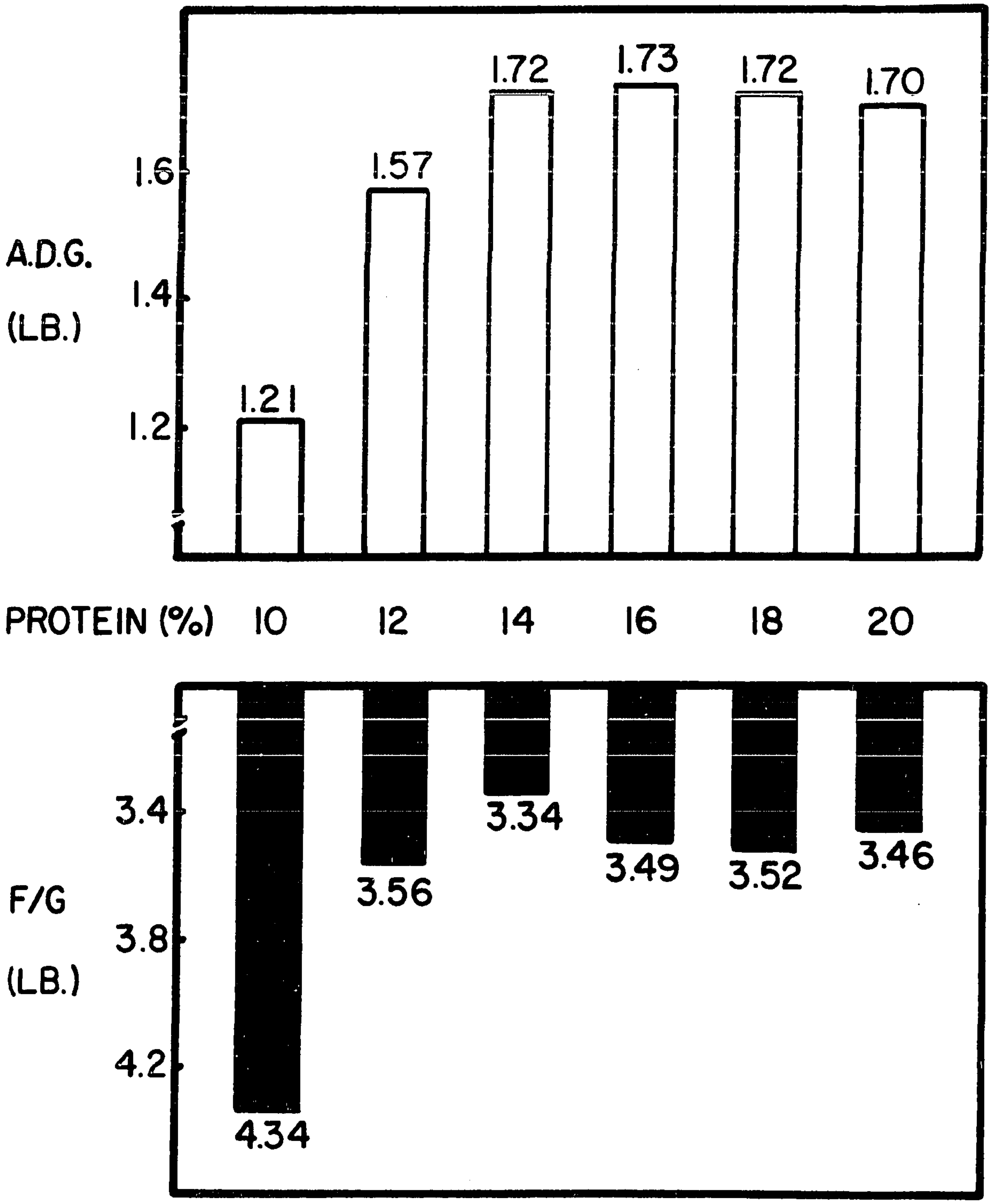
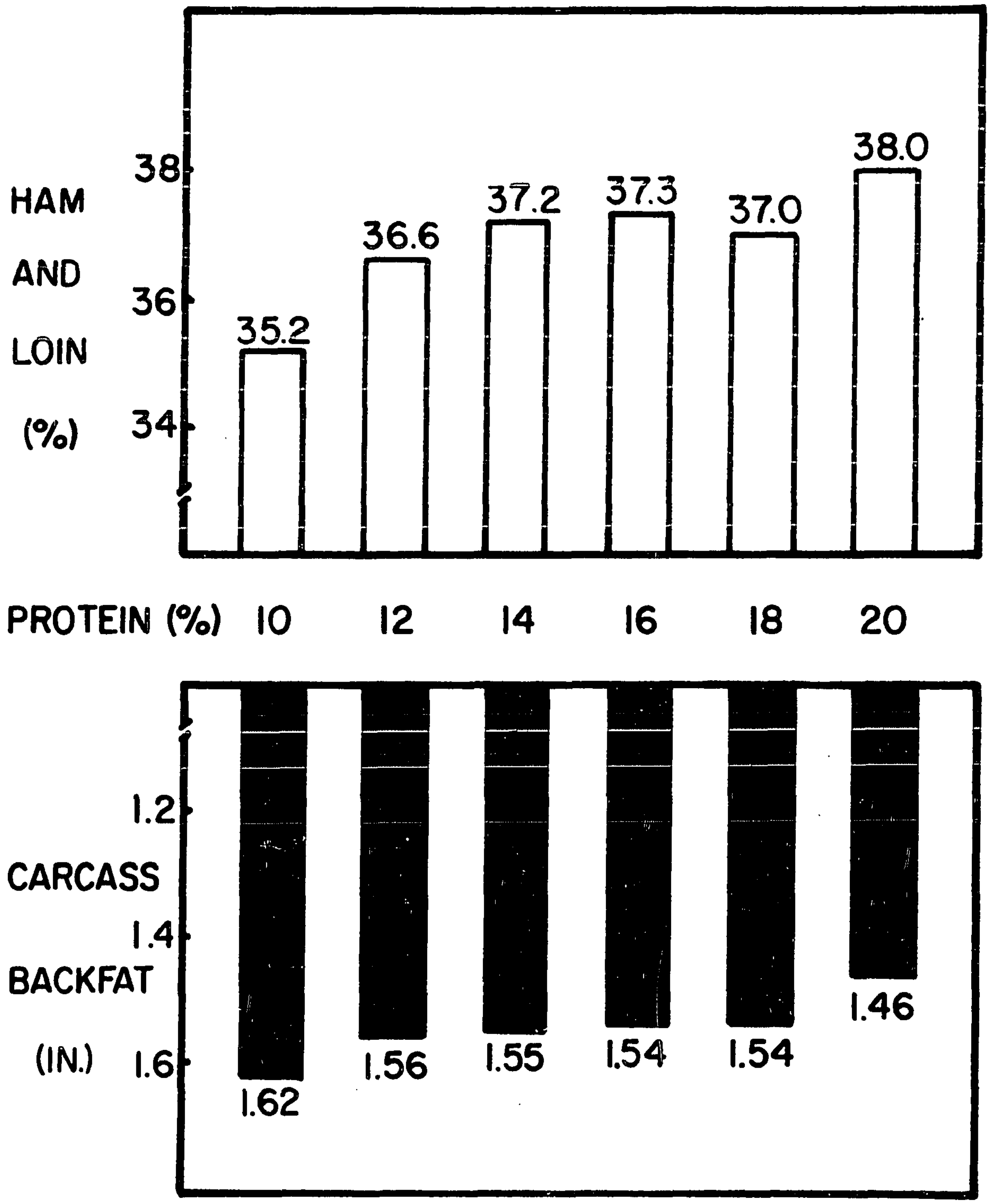

1.21
1.57
1.72
1.73
1.72
1.70
1.6
1.4
1.2
A.D.G.
(LB.)
PROTEIN (%)
10
12
14
16
18
20
3.4
3.8
4.2
F/G
(LB.)
4.34
3.56
3.34
3.49
3.52
3.46

Figure 2. Experiment 6323 - effect of protein level on percent ham and loin, and carcass backfat for the entire experimental period


HAM
AND
LOIN
(%)
38
36
34
35.2
36.6
37.2
37.3
37.0
38.0
PROTEIN (%) 10 12 14 16 18 20
1.2
CARCASS
1.4
BACKFAT
(IN.) 1.6
1.62
1.56
1.55
1.54
1.54
1.46

at the 20, 14 and 14 percent protein levels, respectively, for the 50 to 110, 110 to 205 and 50 to 205 pound periods. Feed required per pound of gain was greater than that noted by Jensen et al. (1955), who obtained maximum feed efficiency at 12 percent protein for the entire period.

There were significant linear and cubic regressions of percent ham and loin on protein level with the maximum percent ham and loin at a level of 20 percent protein. Ashton et al. (1955) also obtained maximum percent lean cuts at 20 percent protein. A significant linear regression of backfat on protein level existed with minimum backfat noted at 20 percent protein. A significant quadratic regression of dressing percent was noted with maximum dressing percent existing at the 12 percent protein level.

Carcass length was not significantly affected by protein level. The lowest number of pigs grading U.S. No. 1 was found at 10 percent protein whereas the highest number was noted at 20 percent protein. Grade did not differ appreciably among the pigs on the remaining treatments.

Experiment 6335 - effect of protein level on performance and carcass quality

Objective The purpose of this experiment was to provide observations on performance and carcass quality to be utilized in the calculation of least cost corn-soybean meal rations for growing-finishing swine. This was a winter trial in contrast to the previous summer trial. Thus, there was interest in a possible seasonal or temperature interaction.

Procedure This study was conducted during the winter months between September 1963 and March 1964. The protein levels of 10, 12, 14, 16, 18 and 20 percent were maintained at a constant level throughout the duration of the experiment.

The experimental population consisted of 120 pigs averaging 51 pounds of body weight. They were allotted to the treatments in the manner explained in the previous experiment.

Carcass data were collected after slaughtering the pigs at a body weight of 205 pounds.

Results and discussion Summaries of average daily gain and feed required per pound of gain are shown in Tables 16 and 17, respectively and in Figure 3. Percent ham and loin and carcass backfat, yield, length and grade are summarized in Tables 18 and 19. Figure 4 illustrates the treatment means for percent ham and loin and carcass backfat. The analysis of variance plan and observed mean squares for all of the criteria are contained in Tables 20 and 21.

There were significant linear and quadratic regressions of average daily gain on protein level for the 51 to 110 pound period with the maximum gain occurring at the 18 percent protein level. Significant linear, quadratic and cubic regressions of average daily gain on protein level existed during the 110 to 205 pound interval and for the entire period with maximum gain at the 14 percent protein level for both periods. Again, adequate response was obtained at the lowest level of protein

Figure 3. Experiment 6335 - effect of protein level on average daily gain and feed required per pound of gain for the entire experimental period

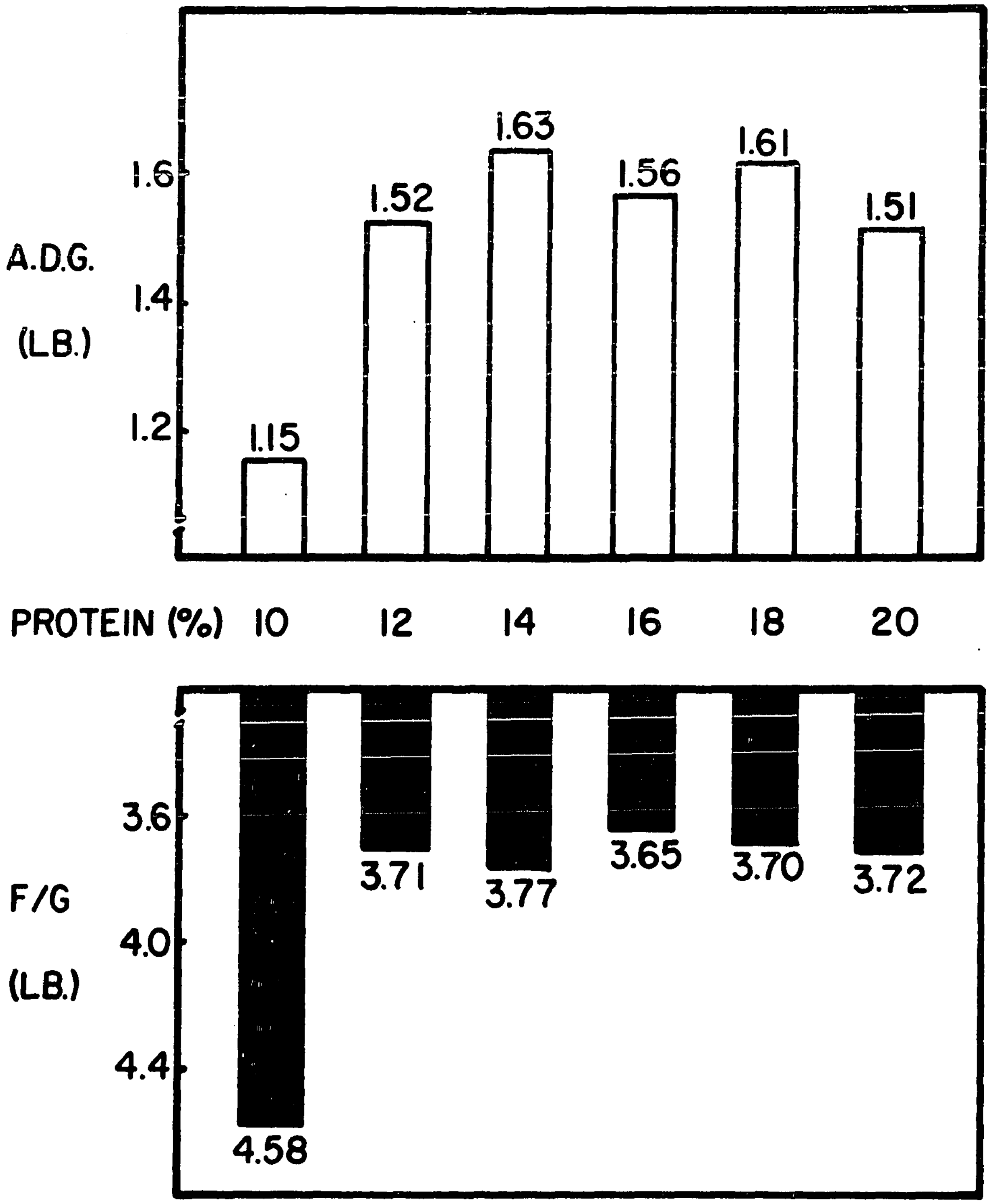
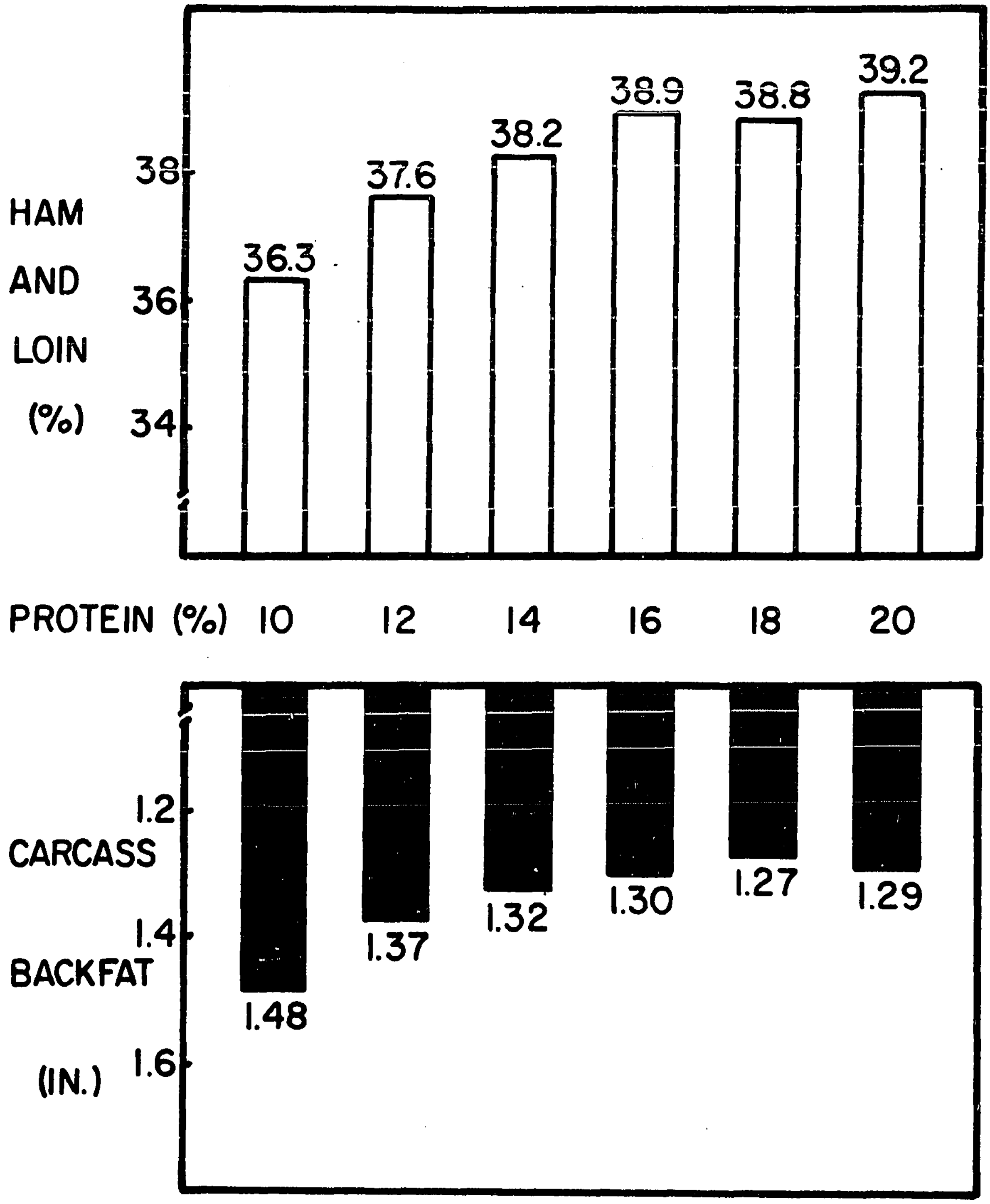

1.63
1.61
1.56
1.52
1.51
1.15
1.6
1.4
1.2
A.D.G.
(LB.)
PROTEIN (%) 10 12 14 16 18 20
3.6
4.0
4.4
F/G
(LB.)
3.71
3.77
3.65
3.70
3.72
4.58

Figure 4. Experiment 6335 - effect of protein level on percent ham and loin, and carcass backfat for the entire experimental period


HAM
AND
LOIN
(%)
38
36
34
36.3
37.6
38.2
38.9
38.8
39.2
PROTEIN (%)
10
12
14
16
18
20
CARCASS
BACKFAT
(IN.)
1.2
1.4
1.6
1.48
1.37
1.32
1.30
1.27
1.29

where the daily gain averaged 1.15 pounds for the entire period. Contrary to the comparison in the first experiment, these results do not agree quite as closely with those of Jensen *et al*. (1955) who obtained a response of 1.47 pounds of average daily gain at the same protein level. However, they also obtained maximum response at the 14 percent protein level for the entire period.

Significant linear, quadratic and cubic regressions of feed required per pound of gain on protein level were determined for each stage of the production period, as well as for the entire period. Maximum feed efficiency was noted at the 20, 12 and 16 percent protein levels, respectively, for the 51 to 110, 110 to 205 and 51 to 205 pound periods. Again, feed required per pound of gain was greater than that noted by Jensen *et al*. (1955), especially at the lowest protein level. They obtained maximum feed efficiency at 12 percent protein for the entire period. However, it should be noted that the pigs in their study were confined to indoor pens, which might have accounted for part of the difference in both rate and efficiency of gain.

There were significant linear and quadratic regressions of percent ham and loin on protein level with the maximum percent ham and loin at a level of 20 percent protein. In contrast, Ashton *et al*. (1955) noted maximum percent lean cuts at 16 percent protein in a similar study. A significant linear regression of backfat on protein level existed with the minimum backfat occurring at 18 percent protein. Maximum dressing percent was noted at 12 and 14 percent protein resulting from a significant quadratic regression of dressing percent on protein level.

Carcass length was significantly increased in a linear manner as the protein level was increased. The lowest number of pigs grading U.S. No. 1 was noted at 10 percent protein whereas the highest number was noted at the 16, 18 and 20 percent protein levels. The number of pigs grading U.S. No. 1 on the 12 and 14 percent protein levels were approximately intermediate to those on the other protein levels.

Experiment 6417 - effect of change in protein level during the growing-finishing period on performance and carcass quality

Objective The purpose of this experiment was to provide observations on performance and carcass quality as affected by a change in protein level; and thus to test the assumption, underlying the least cost ration technique, that the response of the pig in a given weight period exerts a negligible effect on the response in subsequent weight periods.

Procedure One hundred and twenty pigs were subjected to six ration treatments during the summer months of May through September 1964. Allotment was conducted in the manner previously described. Carcass data were again collected on the pigs.

The ration treatments consisted of 10, 13.3, 16.6 and 20 percent protein for the 46 to 110 pound period. Two pens of pigs in each replicate were on the 10 percent level and two pens of pigs in each replicate were on the 20 percent level. During the 110 to 205 pound interval one of the pens previously receiving 10 percent protein in each replicate was switched to 20 percent protein. Similarly, one of the pens previously receiving the 20 percent protein level in each replicate was changed to 9 percent protein. The remaining pens of pigs in each replicate were given 12 percent protein rations. The interest was mainly in the contrast of the reversal of the two extreme protein levels. For example, would the depressing or accelerating effect of the protein level in the early period affect the response in the later period?

Results and discussion Summaries of average daily gain and feed required per pound of gain are shown in Tables 22 and 23, respectively and in Figures 5, 6 and 7. Percent ham and loin and carcass backfat, yield, length and grade are summarized in Tables 24 and 25. Figure 8 illustrates the treatment means for percent ham and loin and carcass backfat. The analysis of variance plan and observed mean squares for all of the criteria are contained in Tables 26, 27 and 28.

There were significant linear and quadratic regressions of average daily gain on protein level during the 46 to 110 pound interval (early) with maximum gain at 20 percent protein. The error mean square for the common variation between

Figure 5. Experiment 6417 - effect of protein level change on average daily gain for the 46 to 110 pound and 110 to 205 pound intervals

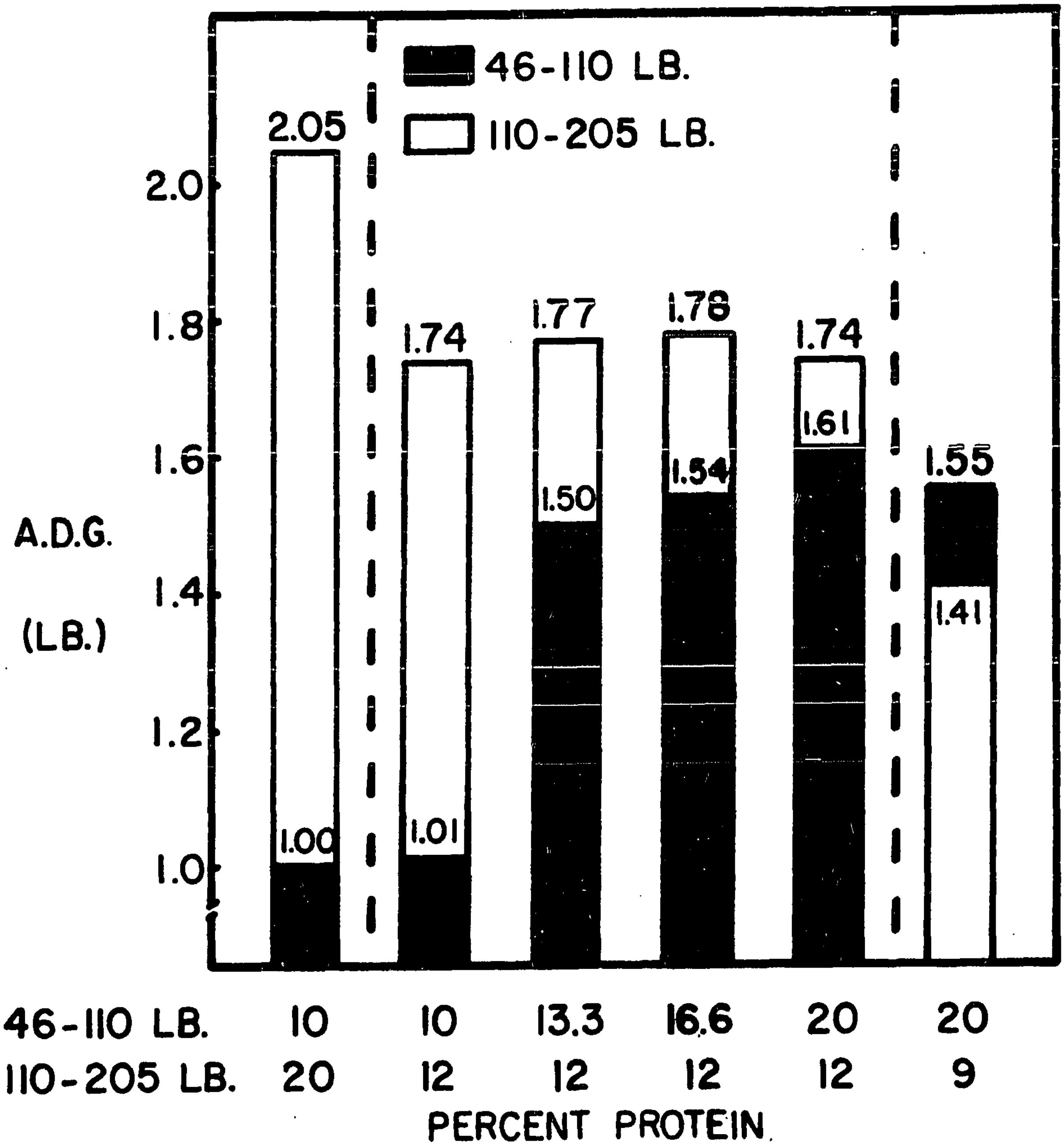
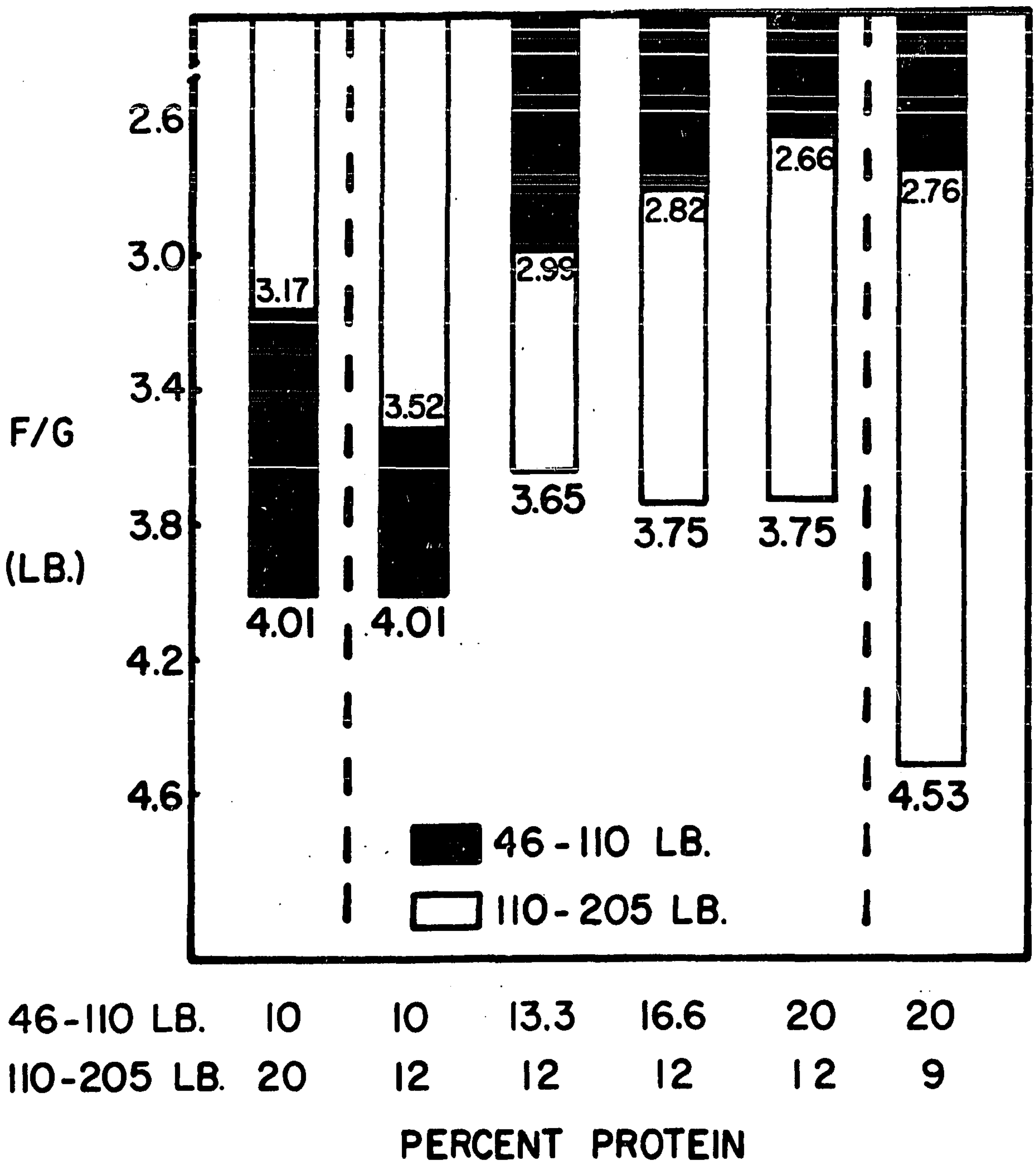

46-110 LB.
110-205 LB.
2.05
1.74
1.77
1.78
1.74
1.61
1.54
1.50
1.55
1.41
1.00
1.01
2.0
1.8
1.6
1.4
1.2
1.0
A.D.G.
(LB.)
46-110 LB. 10 10 13.3 16.6 20 20
110-205 LB. 20 12 12 12 12 9
PERCENT PROTEIN

Figure 6. Experiment 6417 - effect of protein level change on feed required per pound of gain for the 46 to 110 pound and 110 to 205 pound interval



2.6
3.0
3.4
3.8
4.2
4.6
F/G
(LB.)
3.17
4.01
3.52
4.01
2.99
3.65
2.82
3.75
2.66
3.75
2.76
4.53
46-110 LB.
110-205 LB.
46-110 LB. 10 10 13.3 16.6 20 20
110-205 LB. 20 12 12 12 12 9
PERCENT PROTEIN

Figure 7. Experiment 6417 - effect of protein level change on average daily gain and feed required per pound of gain for the entire experimental period

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[a]Percent protein of the rations comprising the experimental treatments.

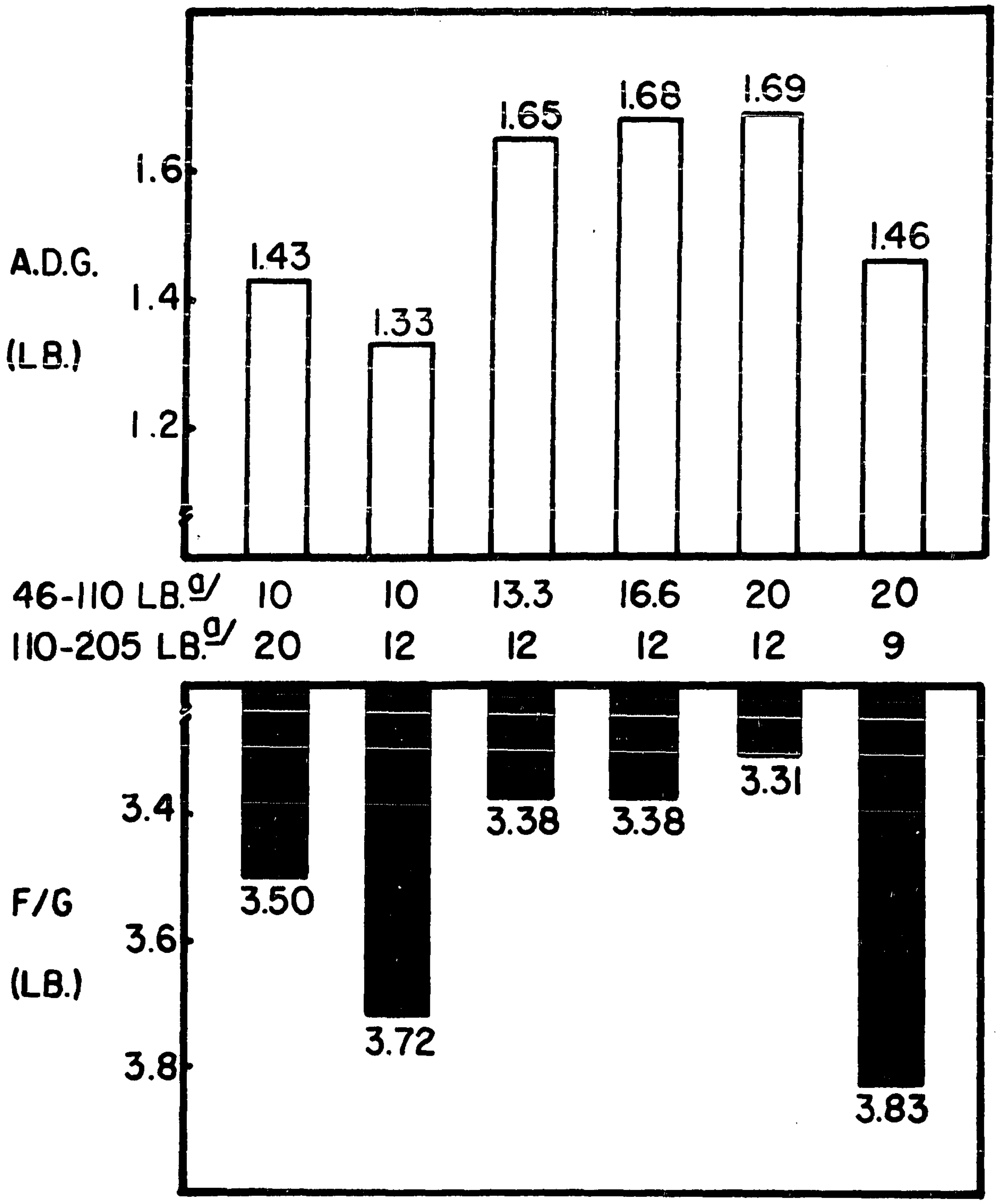
1.43
1.33
1.65
1.68
1.69
1.46
1.6
A.D.G.
1.4
(LB.)
1.2
46-110 LB.a/ 10 10 13.3 16.6 20 20
110-205 LB.a/ 20 12 12 12 12 9
3.4
3.50
3.72
3.38
3.38
3.31
3.83
F/G
3.6
(LB.)
3.8

Figure 8. Experiment 6417 - effect of protein level change on percent ham and loin, and carcass backfat for the entire experimental period

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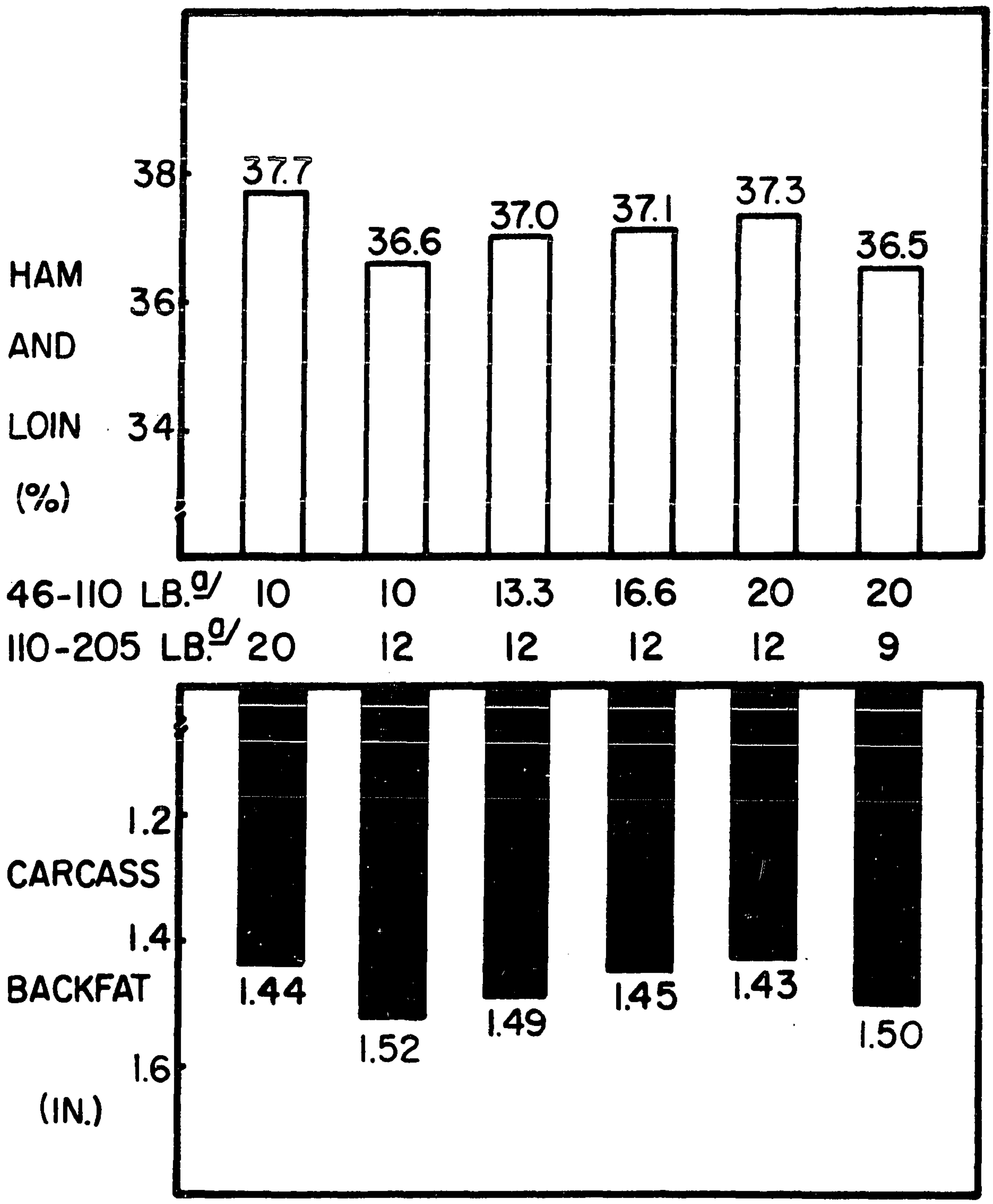
[a]Percent protein of the rations comprising the experimental treatments.


HAM
AND
LOIN
(%)
38
36
34
37.7
36.6
37.0
37.1
37.3
36.5
46-110 LB.a/ 10 10 13.3 16.6 20 20
110-205 LB.a/ 20 12 12 12 12 9
1.2
CARCASS
1.4
BACKFAT
1.6
(IN.)
1.44
1.52
1.49
1.45
1.43
1.50

responses at the two treatments comprising each of the low and high protein levels was significant, mainly due to the variation at the high protein level.

Significantly higher average daily gain was noted during the 110 to 205 pound interval (late) at 20 percent protein when compared to 9 percent protein. Pigs which had been on 20 percent protein during the early period produced lower gains while receiving 9 percent protein during the late period. This indicated a negligible effect from high protein in the early period. The response of the pigs on 20 percent protein (late) was more than double the response which they had shown on 10 percent protein (early), thus indicating no depressing effect from low protein in the early period. The pigs which had been on all four protein levels early and were then switched to 12 percent protein (late) produced strikingly similar gains.

Average daily gain for the entire period was significantly higher for the pigs switched from all of the protein levels to 12 percent protein (carry-over) when compared with the two extreme changes in protein levels. However, the pigs receiving 10 percent protein early and 12 percent protein later produced the lowest gain of the pigs on any of the treatments. There were significant linear and quadratic regressions of average daily gain on protein level for the pigs on the carry-over treatments.

Significant linear, quadratic and cubic regressions of feed required per pound of gain on protein level were found during the early period with maximum feed efficiency occurring at the 20 percent protein level. The error mean square for the common variation between responses at the two treatments comprising each of the low and high protein levels was significant, mainly due to the variation at the 20 percent protein level.

Significantly less feed was required per pound of gain during the late period at 20 percent protein when compared to the 9 percent protein level. There was a significant linear regression of feed required per pound of gain on protein level for the pigs on the 12 percent protein level during the late period, indicating some effect from the higher protein levels fed during the early period. Pigs which had been on 10 percent protein during the early period produced a marked improvement in feed efficiency on the 20 percent protein level later, parallelling the trend in average daily gain. Pigs which were on the 20 percent protein level early and were switched to 9 percent protein required considerably more feed per pound of gain than did those switched to the 12 percent protein level later.

Feed required per pound of gain for the entire period was significantly higher for the pigs receiving 20 percent (early) and 9 percent (late) protein when compared to those on the 10 percent (early) and 20 percent (late) protein levels, indicating very little effect from protein levels in the early period. There were significant linear and quadratic regressions of feed required per pound of gain on protein level for the pigs on the carry-over treatments parallelling the trend in average daily gain.

Percent ham and loin was significantly higher for pigs on the 10 percent (early) and 20 percent (late) protein level when compared to the 20 percent (early) and 9 percent (late) protein level. Pigs on the carry-over treatments exhibited little difference in percent ham and loin. Thus, response to protein level in the late period was affected little by the response in the early period. A significant linear regression of carcass backfat on protein level existed for the pigs on the carry-over treatments, indicating an effect of increasing protein level on decreasing backfat from the early period. Neither carcass yield nor length were significantly affected by protein level. The lowest number of pigs grading U.S. No. 1 was found at the 10 (early) and 12 (late) percent protein level treatment. Grade did not differ appreciably among the pigs on the remaining treatments.

Experiments 6323, 6335 - effect of combining experiments over seasons on performance, percent ham and loin, and time

Objective The purpose of this analysis was to combine the two experiments utilized in calculation of least cost corn-soybean meal rations for growing-finishing swine. Therefore, if no season times protein level interaction existed, the data could be combined to produce one set of substitution rates and least cost rations.

Procedure Initial tests of homogeneity of error variance between seasons for the criteria which were combined indicated that the samples were from similar populations. Therefore, the data for the effect of protein level on average daily gain, feed required per pound of gain, percent ham and loin, and days required over the production period were combined and statistically analyzed for the entire experimental period. Summaries of the averages of the four criteria are shown in Table 29. The analysis of variance plan and observed mean squares for all of the criteria are contained in Table 30.

Results and discussion There were no significant season times protein level interactions for any of the criteria tested. Thus, it was evident that the response to the level of protein in the winter was similar to the response in the summer. The sums of squares for this term were pooled with the sums of squares for the replications/seasons times protein level to provide an error mean square for testing the protein level effect.

There were significant linear, quadratic and cubic regressions of average daily gain and feed required per pound of gain on protein level. Maximum gains and feed efficiency were attained at a protein level of 14 percent. These results agree closely with the results previously noted in the individual experiments. Jensen et al. (1955) combined the two experiments corresponding to the experiments reported herein. They noted maximum rate and efficiency of gain at the 16 and 12 percent protein levels, respectively, for the entire period.

Significant linear, quadratic and cubic regressions of percent ham and loin on protein level were noted with maximum percent ham and loin at 20 percent protein. Again, there is reasonably close agreement among these results and the individual experimental results.

Significant linear, quadratic and cubic regressions of time on protein level also existed. The greatest number of days required over the production period was noted at the 10 percent protein level.

The Production Function

Choice of function

The logics of nutrition and economics must be considered when selecting the appropriate function relating the body weight gain of pigs to corn and soybean meal inputs. Statistics may be used to further differentiate the functions, given that they are similar with respect to nutritional and economical logic.

Growing pigs require large amounts of protein for the building of tissues. As they mature in age and weight the requirement for protein declines and more carbohydrate feeds are needed to provide energy for maintenance and fat production. Thus, there is a shift in the requirement for protein relative to the requirement for energy, implying a reduction in the rate at which soybean meal replaces corn in the ration.

The quantities of corn and soybean meal in the ration can be varied widely, thus providing a range of rations on which a pig will attain market weight. However, the ration should be properly supplemented with minerals and vitamins and should remain within a reasonable protein percentage range in order to promote growth. Extremes in protein percentage of the ration will create a depressing effect on the rate of growth during the production period. A ration low in protein level, for example all corn, will elicit an extremely slow growth rate throughout the growing-finishing period. Feed intake of a ration completely composed of corn would not be sufficient to provide the amounts of protein needed for adequate growth. An extremely high protein percentage in the ration will produce rapid early gains, but will depress the growth rate in later stages.

Therefore, the choice of the appropriate function is dependent upon several important concepts. The production function should express an increasing elasticity of production for corn as the pig matures in weight. Conversely, the function should express a declining elasticity of production for soybean meal as the pig becomes heavier. The function should also allow, but not force, corn to be expressed as a limitational factor of production. Furthermore, the function should allow the mixture of the two resources, corn and soybean meal, to be changed as the gain of the pig proceeds over the production surface.

The two types of equations which have been examined as alternatives are the quadratic function and the square root function, a modified form of the quadratic. The quadratic forms express changing elasticities of production for corn and soybean meal and will allow, but not force, either resource to be expressed as limiting factors of production. Modification of the quadratic by replacing the second power terms with square root terms results in a function which declines less rapidly with increasing inputs of corn and soybean meal. The crossproduct terms allow the expression of the marginal productivities (used in deriving substitution rates) as a function of the inputs of both corn and soybean meal. Thus, the logics of nutrition and economics are similar for the two functions.

A third type of function fitted to the data in Experiment 6323 was the Cobb-Douglas. However, this function was rejected because it does not permit changing rates of substitution over the production period. This problem may be resolved by fitting separate functions to separate gain intervals in the production period. However, it was not feasible to fit separate functions to the many intervals into which it was desired to divide the production period. Also, the coefficient of determination for the Cobb-Douglas was lower than for the quadratic forms.

<u>Experiment 6323</u> Following are the equations estimated by regression analysis:

$$(1.1)\quad \text{Square root: } Y = -12.411552 + .064642C - .661199S + 1.551790\sqrt{C} + 4.306910\sqrt{S} + .655558\sqrt{C}\sqrt{S}$$

$$(1.2)\quad \text{Quadratic: } Y = 1.4090046 + .2787371C + .6972671S - .00013026C^2 - .00415128S^2 + .00083795CS$$

Table 31 contains the analysis of variance plan and observed mean squares for the functions. Correlation coefficients, and standard errors and significance tests of the regression coefficients may be found in Table 32.

The regression of gain (Y) on corn (C) and soybean meal (S) consumption was highly significant for both functions. All of the regression coefficients for both functions were significant at a probability of .01 or less.

Although the coefficients of determination for both functions were extremely high, the square root function explained a greater proportion of the variation in gain, .9939, in comparison to .9917 for the quadratic function.

<u>Experiment 6335</u> The estimates for the two equations are as follows:

(1.3) Square root: $Y = -13.080066 + .082158C - .635703S + 1.167440\sqrt{C} + 5.610180\sqrt{S} + .548823\sqrt{C}\sqrt{S}$

(1.4) Quadratic: $Y = 1.7390616 + .2615908C + .6922792S - .000106000C^2 - .003484645S^2 + .00058144CS$

Table 33 contains the analysis of variance plan and observed mean squares for the functions. Correlation coefficients, and standard errors and significance tests of the regression coefficients are presented in Table 34.

The regression of gain on corn and soybean meal was highly significant for both functions. All of the regression coefficients for both functions were significant at a probability of .01 or less.

Again, though the coefficients of determination were extremely high for both functions, the square root function accounted for a greater proportion of the variation in gain, .9887, in comparison to .9852 for the quadratic function.

Combined data   The interest in combining the data of the two experiments stemmed from the desire for representation of both the winter and summer seasons by a single set of substitution rates and least cost rations. After appropriate statistical testing indicated no significant season times protein level interaction, as explained in an earlier section, the data were combined.

The estimates for the two equations are as follows:

(1.5) Square root: $Y = -15.113736 + .065790C - .732159S + 1.46890\sqrt{C} + 5.73391\sqrt{S} + .617246\sqrt{C}\sqrt{S}$

$$(1.6)\quad \text{Quadratic:}\quad Y = 1.211804 + .2724238C + .7088003S - .00012157C^2 - .00384327S^2 + .00067205CS$$

Table 35 contains the analysis of variance plan and observed mean squares for the functions. Correlation coefficients, and standard errors and significance tests of the regression coefficients are shown in Table 36.

The regression of gain on corn and soybean meal was highly significant for both functions. All of the regression coefficients for both functions were significant at a probability of .01 or less.

Once again, the coefficients of determination for both functions were extremely high. The square root function again explained a greater proportion of the variation in gain, .9882, in comparison to .9867 for the quadratic function.

Since the theoretical logics of nutrition and economics were similar for both functions, other criteria were chosen for selection of the appropriate function. Results of the determination of substitution rates indicated that the nutritional logic of the quadratic function was not consistent in practice with that expected in theory. The substitution rates of soybean meal for corn derived from the quadratic function were increasing for the 10, 11, 12 and 13 percent protein levels as the pig gained in weight. Woodworth (1954) found similar behavior in the substitution rates of a quadratic function in a previous study. Because the erratic property of the function in this present study was not consistent with nutritional logic, the quadratic function was rejected in favor of the square root function.

The square root function also accounted for slightly more variation in gains than did the quadratic, creating another reason for selection of the square root function. Furthermore, the square root function declines less rapidly at high levels of feed inputs. Since the fit of the function was better, this indicated that rate of gain actually declined less rapidly at large feed inputs than would be expected with the quadratic function. Therefore, the square root function was chosen to represent the relation between gains and feed consumption in the individual as well as combined experiments.

The fit of the function to the 10 and 20 percent protein levels was plotted against the experimental observations for these same protein levels. It was believed that the function would not fit the extreme levels as closely as it would the intermediate protein levels. Figures 9 and 10 illustrate that the function closely estimates the extreme protein levels in Experiment 6323.

The fit of the function to the extreme protein levels in Experiment 6335 may be found in Figures 12 and 13. It appears that the function slightly overestimates the data for the 10 percent protein level at lower feed inputs in this experiment. The function fits the 20 percent protein level quite closely.

Figures 15 and 16 indicate that the function closely estimates the extreme protein levels for the combined data.

The functions representing the 10, 12, 14, 16, 18 and 20 percent protein levels were then plotted on one figure for the purpose of comparison. However, the lines denoting the 14, 16, 18 and 20 percent protein levels were proximate and appeared to blend at various points throughout the figure. The 16 percent level was chosen to represent the 14, 16, 18 and 20 percent levels in the figure. Thus, the functions representing the actual extremes in protein levels, 10 and 16 percent, as well as the intermediate 12 percent level, were plotted. They are represented in Figures 11, 14 and 17, respectively, for Experiments 6323, 6335 and the combined data. The function estimates greater gain in Experiment 6323 (summer) than for Experiment 6335 (winter) at equal feed inputs for the three protein levels. The function for the combined data is approximately intermediate to those of the individual experiments for each protein level.

Gain contours

The production function may be represented by a line drawn in a three dimensional figure relating body weight gain to corn and soybean meal consumption. Corn and soybean meal would be represented on the two axes laying in the plane of the paper and gain would be on the axis projected at a right angle from the plane. A series of proximate lines drawn over the whole diagram would approximate the production surface.

Figure 9. Experiment 6323 - growth curve derived from the square root function (equation 1.1) for the 10 percent protein level

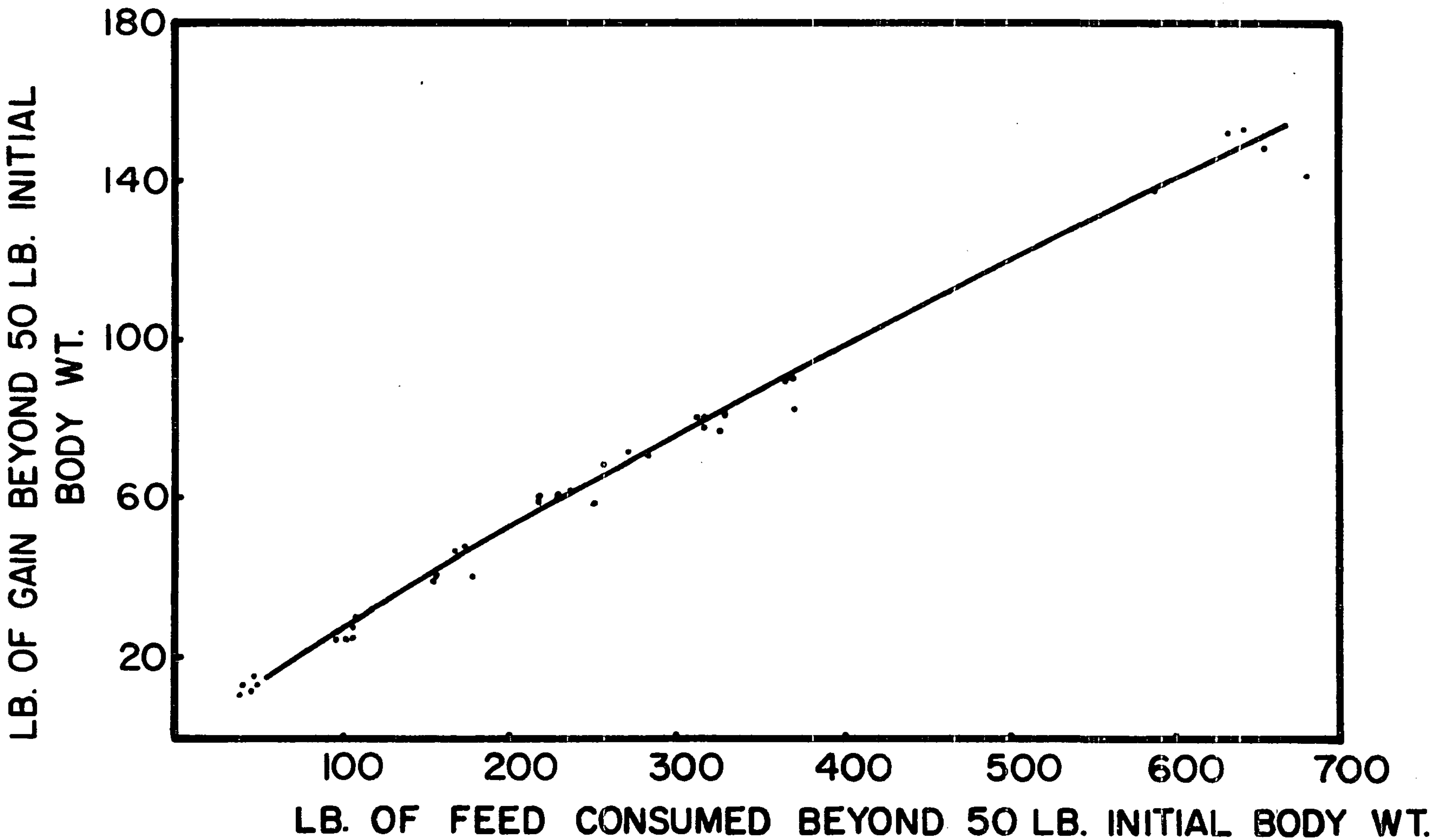

180
140
100
60
20
100
200
300
400
500
600
700
LB. OF GAIN BEYOND 50 LB. INITIAL BODY WT.
LB. OF FEED CONSUMED BEYOND 50 LB. INITIAL BODY WT.

Figure 10. Experiment 6323 - growth curve derived from the square root function (equation 1.1) for the 20 percent protein level

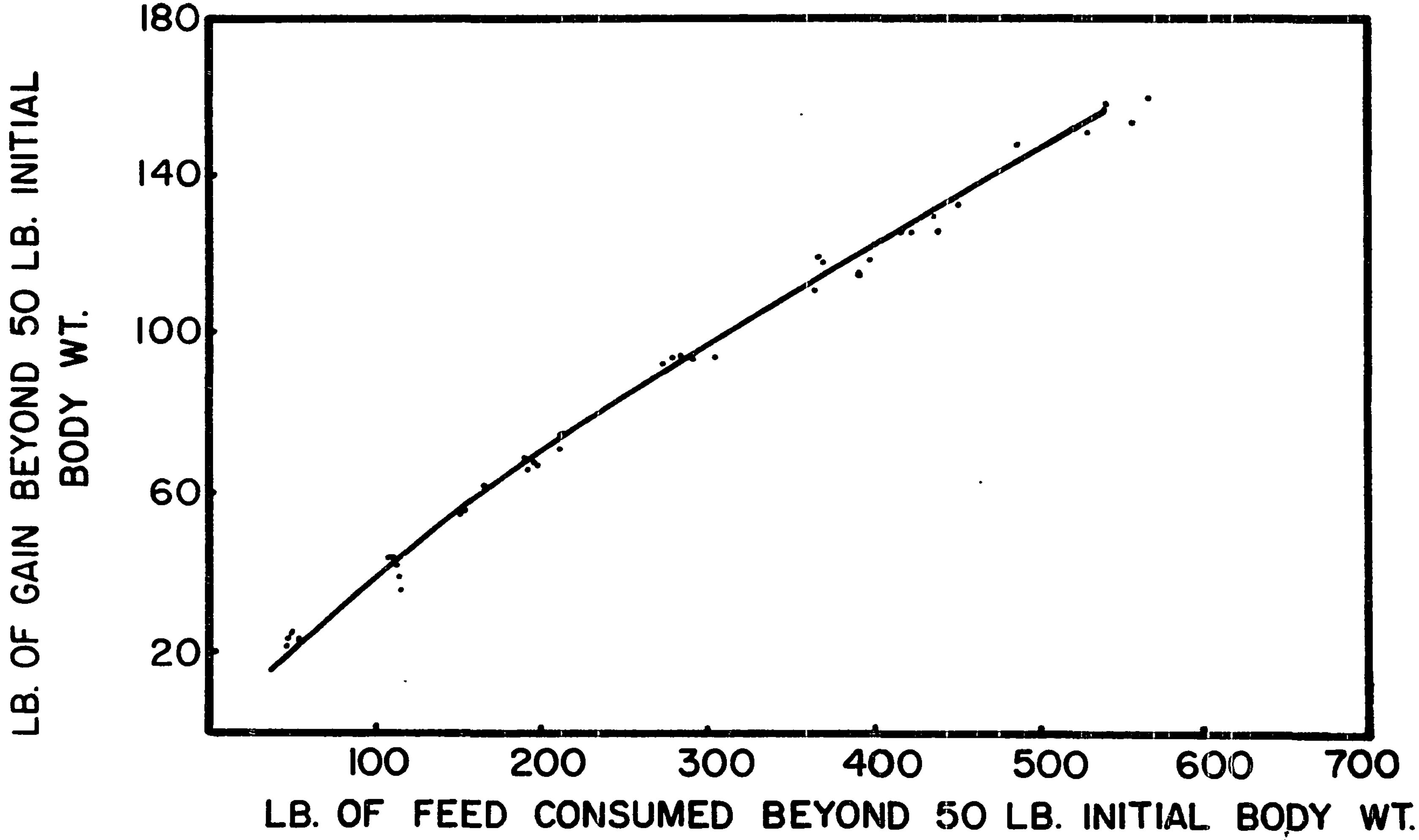
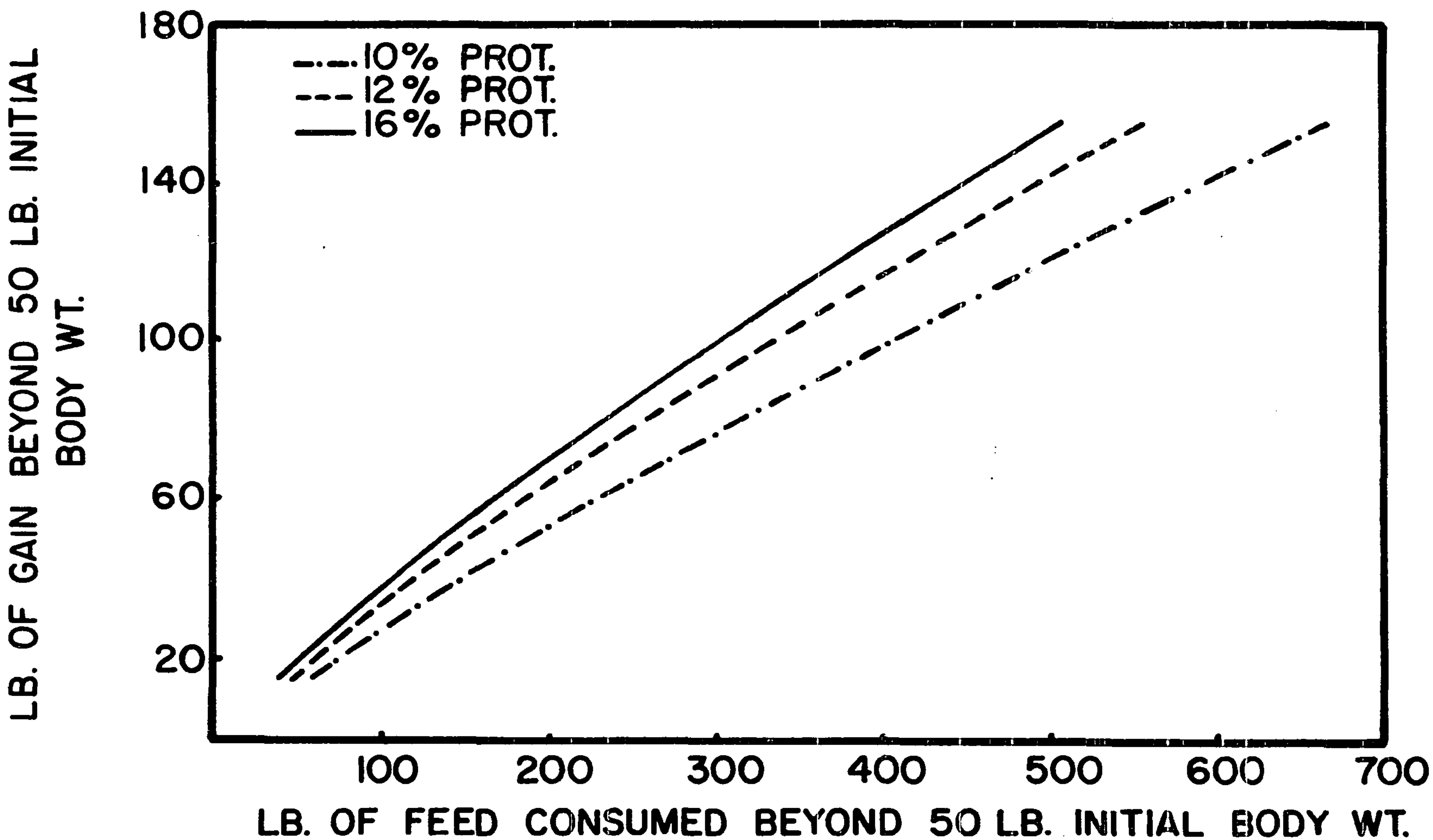

180
140
100
60
20
100
200
300
400
500
600
700
LB. OF GAIN BEYOND 50 LB. INITIAL BODY WT.
LB. OF FEED CONSUMED BEYOND 50 LB. INITIAL BODY WT.

Figure 11. Experiment 6323 - comparison of growth curves derived from the square root function (equation 1.1) for the 10, 12 and 16 percent protein levels



10% PROT.
12% PROT.
16% PROT.
180
140
100
60
20
100
200
300
400
500
600
700
LB. OF GAIN BEYOND 50 LB. INITIAL BODY WT.
LB. OF FEED CONSUMED BEYOND 50 LB. INITIAL BODY WT.

Figure 12. Experiment 6335 - growth curve derived from the square root function (equation 1.3) for the 10 percent protein level

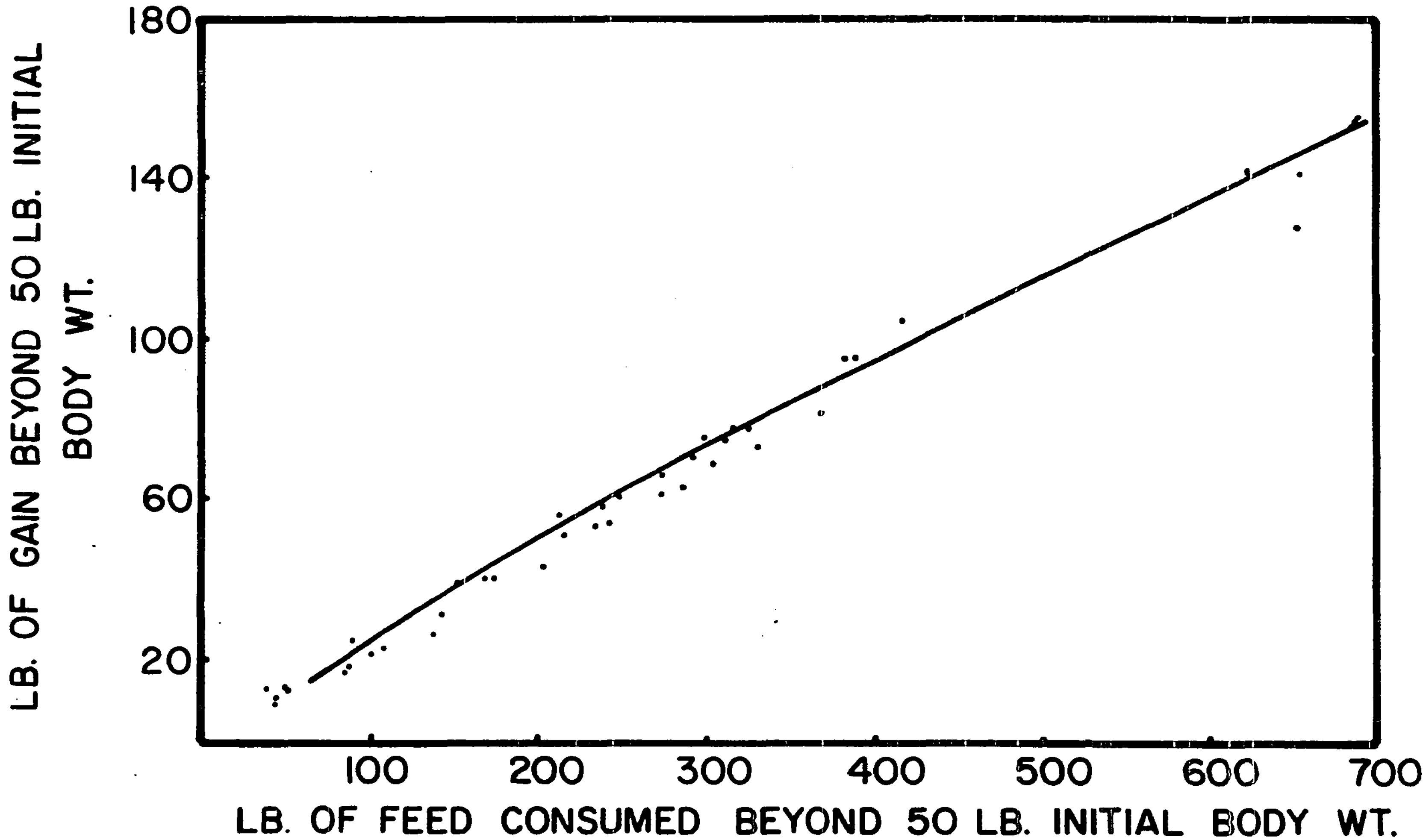

LB. OF GAIN BEYOND 50 LB. INITIAL BODY WT.
180
140
100
60
20
100
200
300
400
500
600
700
LB. OF FEED CONSUMED BEYOND 50 LB. INITIAL BODY WT.

Figure 13. Experiment 6335 - growth curve derived from the square root function (equation 1.3) for the 20 percent protein level

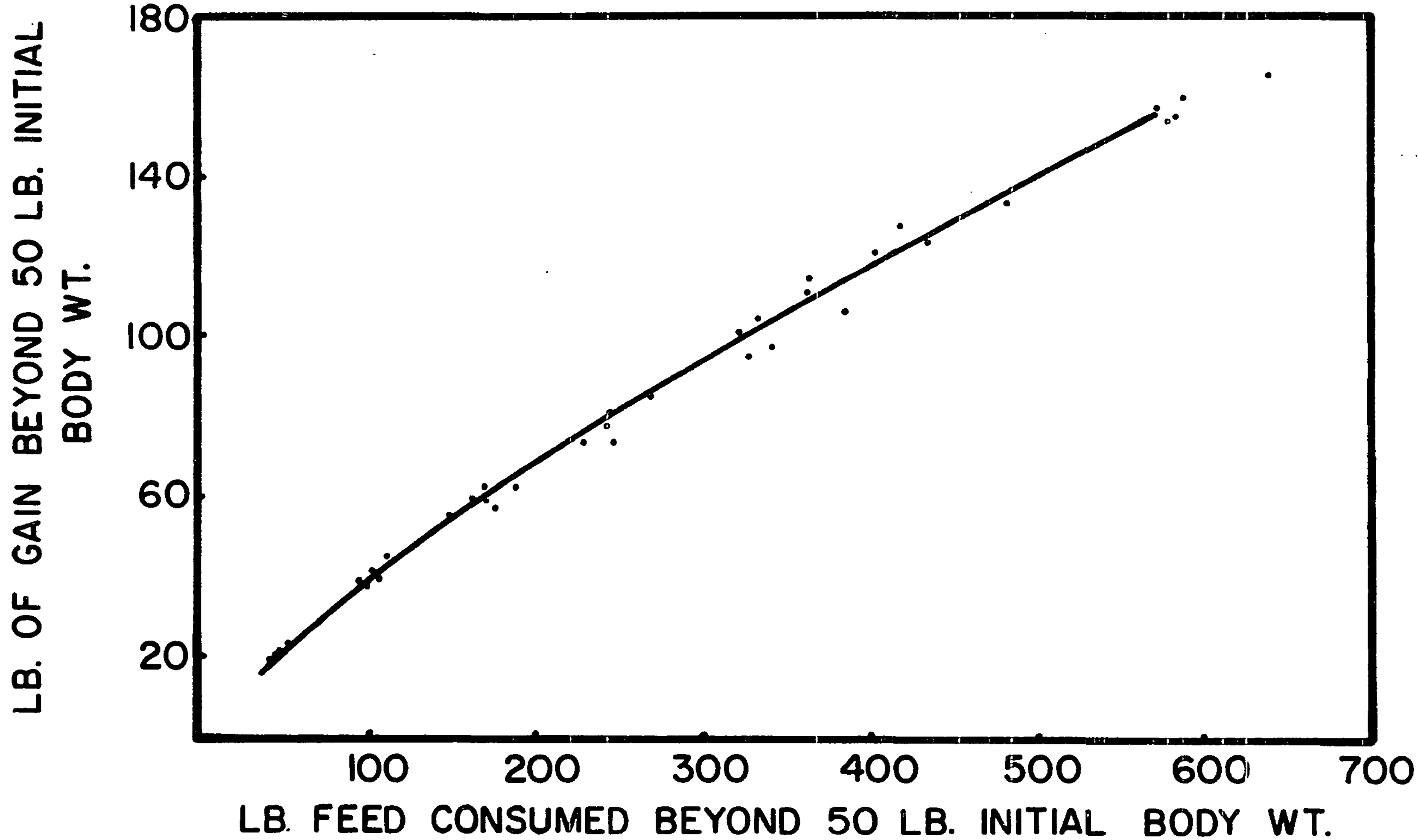
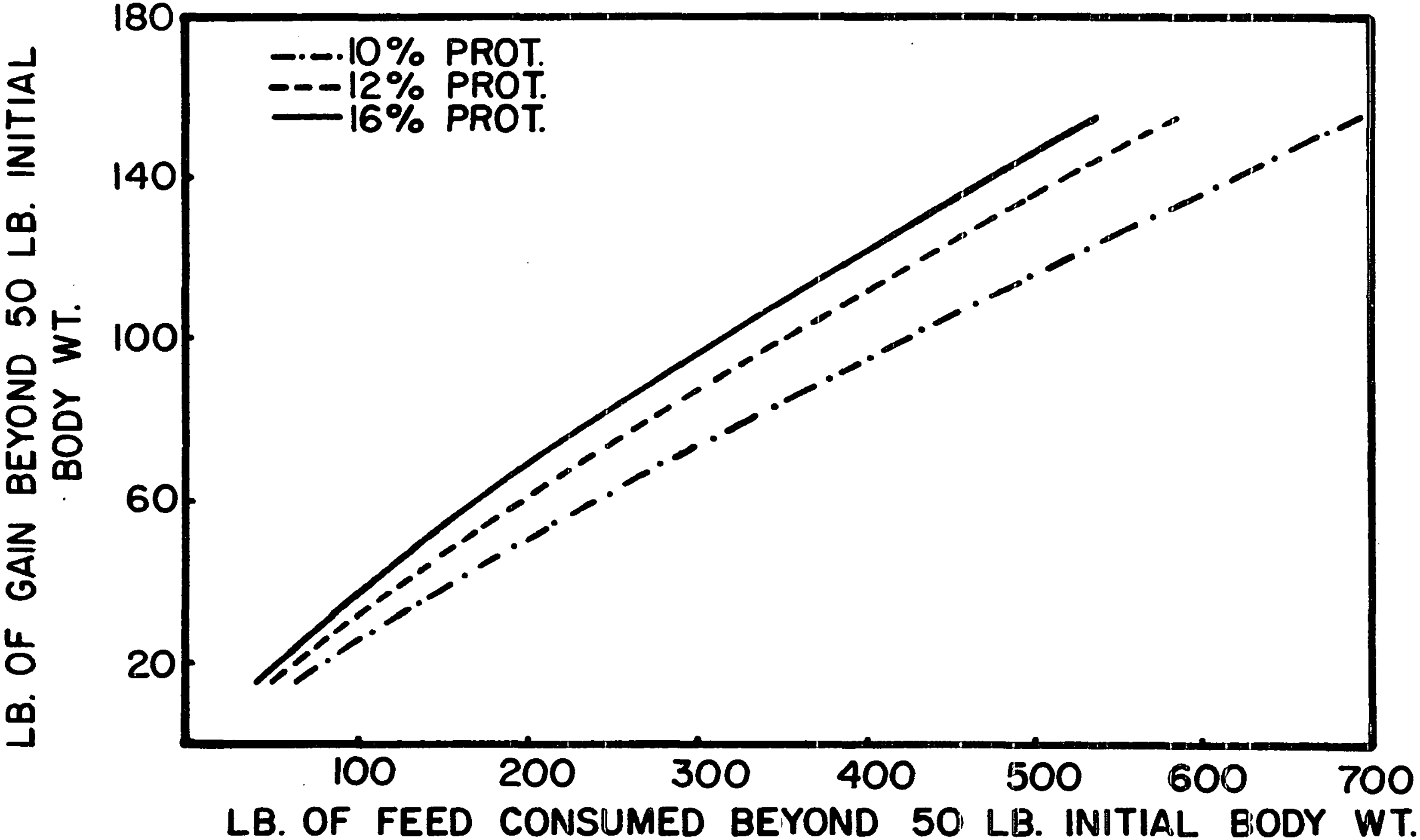

LB. OF GAIN BEYOND 50 LB. INITIAL BODY WT.
180
140
100
60
20
100
200
300
400
500
600
700
LB. FEED CONSUMED BEYOND 50 LB. INITIAL BODY WT.

Figure 14. Experiment 6335 - comparison of growth curves derived from the square root function (equation 1.3) for the 10, 12 and 16 percent protein levels



10% PROT.
12% PROT.
16% PROT.
LB. OF GAIN BEYOND 50 LB. INITIAL BODY WT.
180
140
100
60
20
100
200
300
400
500
600
700
LB. OF FEED CONSUMED BEYOND 50 LB. INITIAL BODY WT.

Figure 15. Combined experiments 6323, 6335 - growth curve derived from the square root function (equation 1.5) for the 10 percent protein level

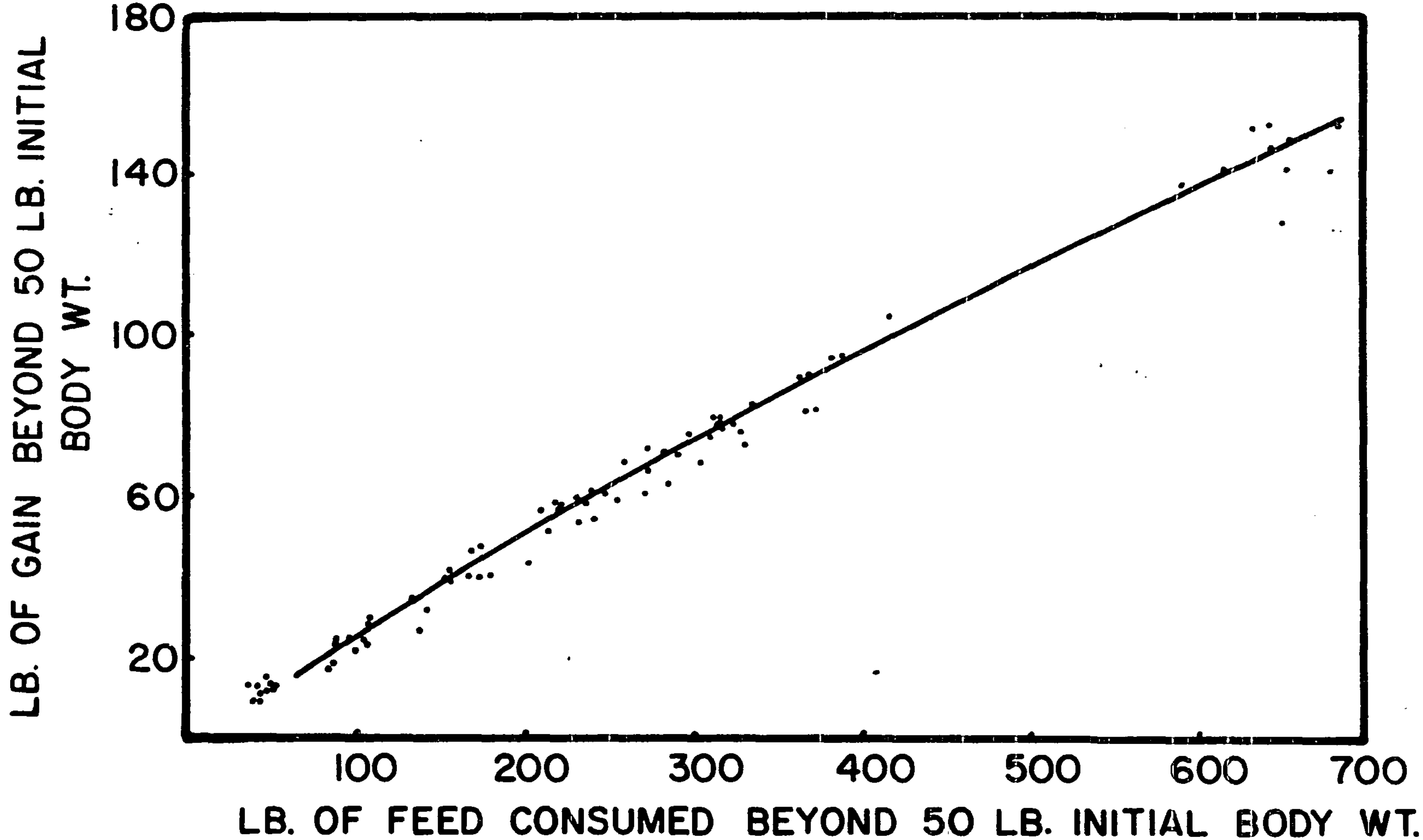

LB. OF GAIN BEYOND 50 LB. INITIAL BODY WT.
180
140
100
60
20
100
200
300
400
500
600
700
LB. OF FEED CONSUMED BEYOND 50 LB. INITIAL BODY WT.

Figure 16. Combined experiments 6323, 6335 - growth curve derived from the square root function (equation 1.5) for the 20 percent protein level

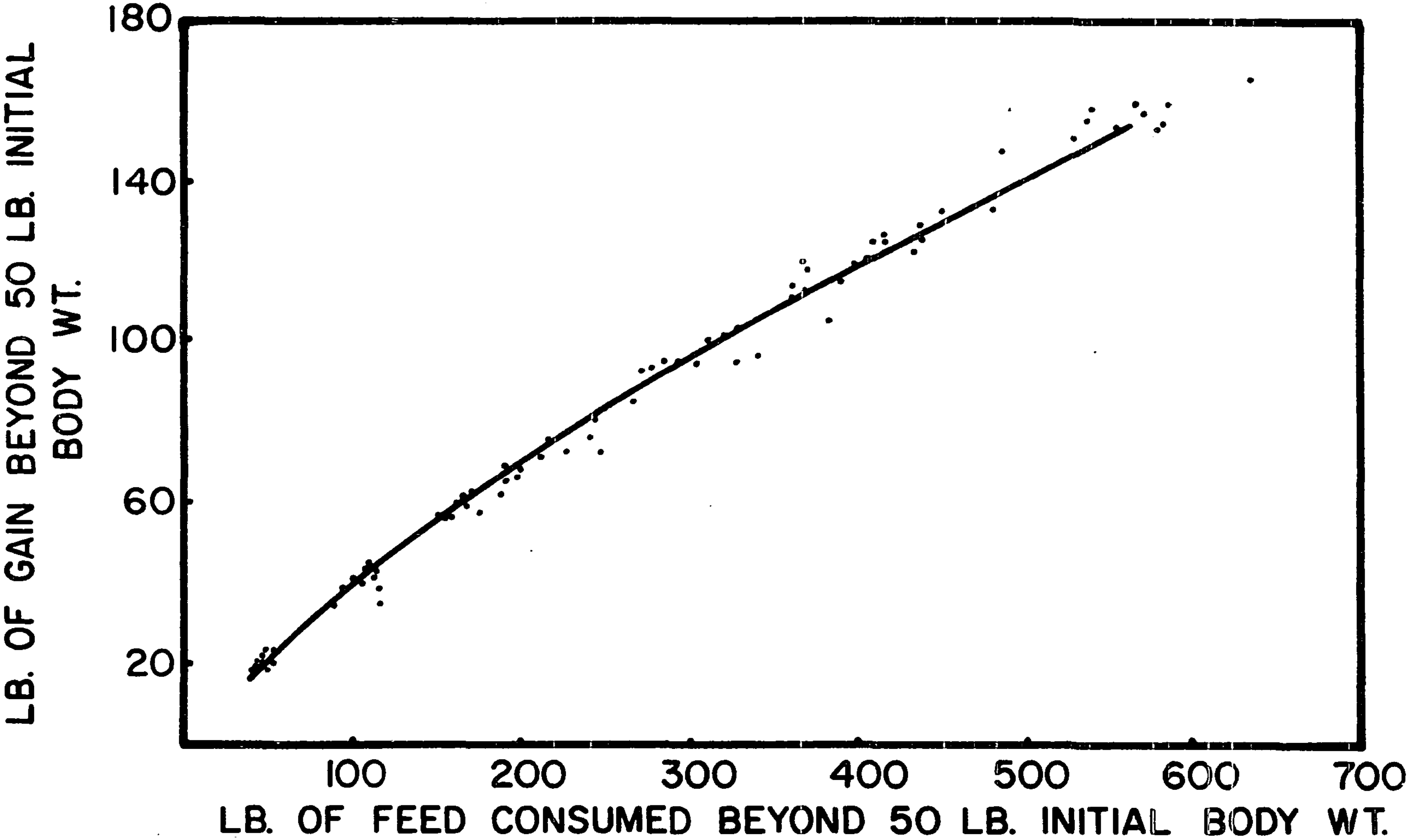
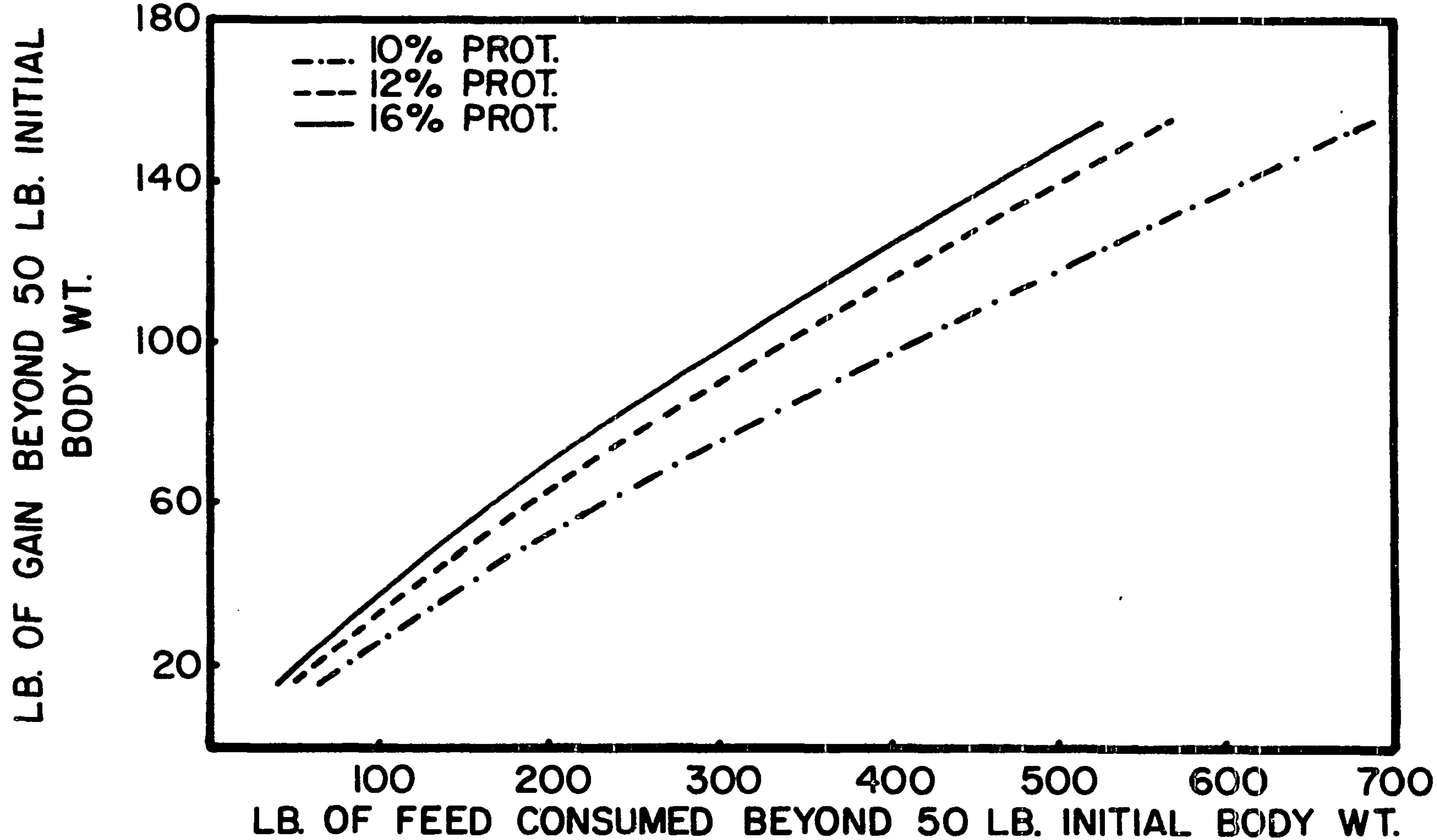

180
140
100
60
20
LB. OF GAIN BEYOND 50 LB. INITIAL BODY WT.
100
200
300
400
500
600
700
LB. OF FEED CONSUMED BEYOND 50 LB. INITIAL BODY WT.

Figure 17. Combined experiments 6323, 6335 - comparison of growth curves derived from the square root function (equation 1.5) for the 10, 12 and 16 percent protein levels



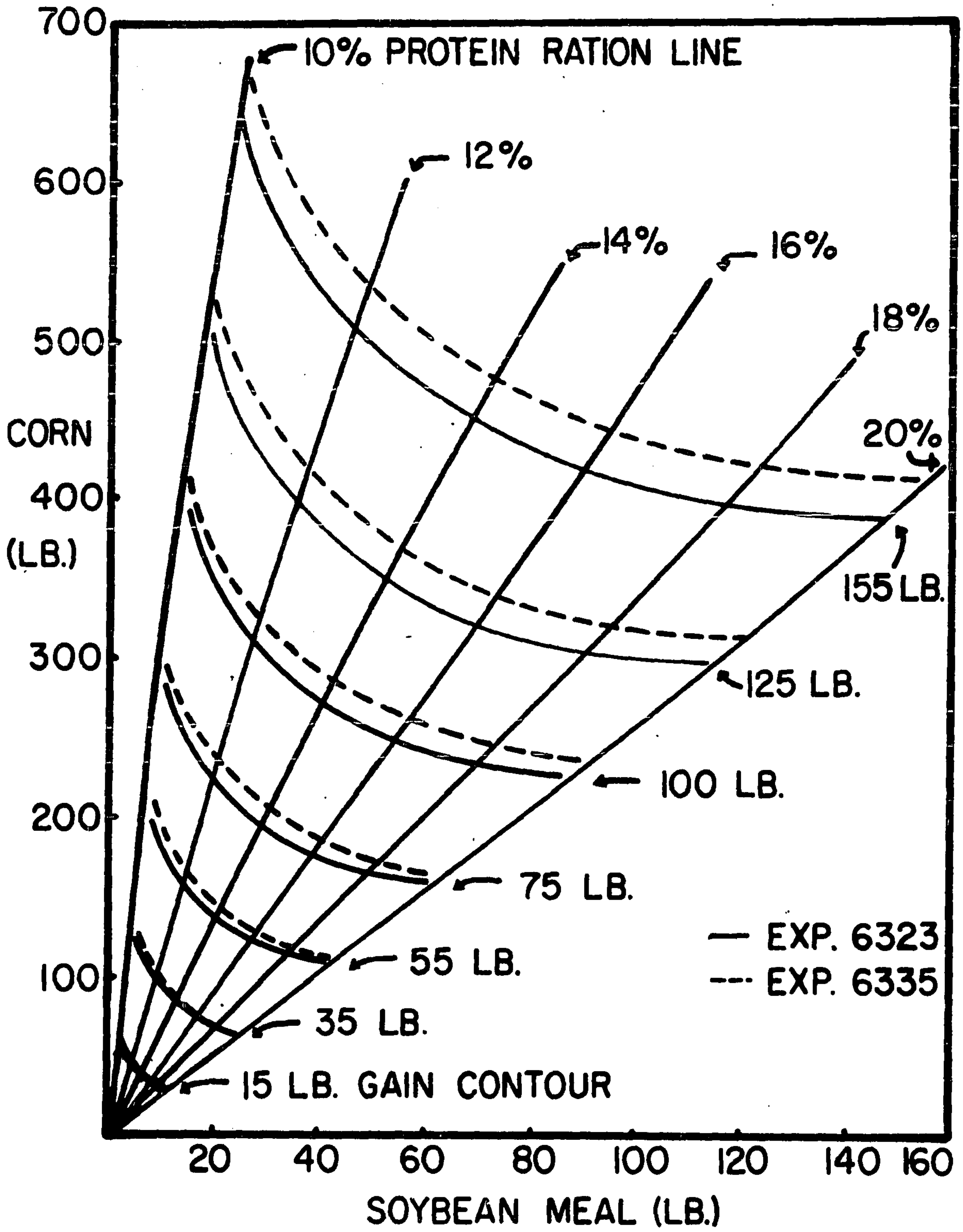
10% PROT.
12% PROT.
16% PROT.
LB. OF GAIN BEYOND 50 LB. INITIAL BODY WT.
180
140
100
60
20
100
200
300
400
500
600
700
LB. OF FEED CONSUMED BEYOND 50 LB. INITIAL BODY WT.

A two dimensional drawing of the production surface can then be produced by joining all points equi-distant from the base plane in a manner similar to the mapping of land surface area. Corn and soybean meal would be represented on the two axes. Such a line is called an isoquant or isoproduct contour (gain contour) since it represents the many combinations of corn and soybean meal that would produce equal amounts of gain.

The contour maps which have been estimated from the square root functions in each of the individual experiments are illustrated in Figure 18. The gain contours of 15, 35, 55, 75, 100, 125, and 155 pounds represent the amount of gain beyond 50 pounds of initial body weight. As it was previously mentioned, they were selected to approximate the gain which might be expected at intervals of two weeks. Protein levels differing by one unit from 10 to 20 percent were utilized in the calculation of the data. However, only the even numbered protein levels are illustrated in Figure 18 for the sake of simplicity.

The points on the contours denoting various protein levels were derived in the following manner. The terms representing corn in the production functions were replaced by the term (R x S). Soybean meal was represented by S, and R represented the ratio of corn to soybean meal for the various percentages of protein. The production function was then solved for soybean meal in terms of gain and the ratios. The quantities of soybean meal required to produce the desired gain were

Figure 18. Experiments 6323, 6335 - comparison of gain contours which illustrate the combinations of corn and soybean meal required to produce given quantities of gain


10% PROTEIN RATION LINE
12%
14%
16%
18%
20%
155 LB.
125 LB.
100 LB.
75 LB.
55 LB.
35 LB.
15 LB. GAIN CONTOUR
— EXP. 6323
--- EXP. 6335
CORN (LB.)
SOYBEAN MEAL (LB.)
700
600
500
400
300
200
100
20
40
60
80
100
120
140
160

calculated by substituting the amount of gain at each contour and the ratio for the protein levels into the contour equation.

The contours for Experiment 6335 (winter) are situated at larger corn and soybean meal inputs than those for Experiment 6323 (summer), as noted in Figure 18. This indicates that smaller inputs of corn and soybean meal were required to produce an equal amount of gain in the summer experiment. This is consistent with the usual observation of an increased amount of feed required per pound of gain during the colder season.

Marginal productivity of feed

The marginal productivity of feed represents the added amount of gain which is produced by an added amount of feed for incremental outputs of gain or inputs of feed. In other words, the marginal quantity represents the rate of increase in body weight gain resulting from increased feed inputs. Therefore, it is similar to the reciprocal of the feed efficiency term, except that it is a marginal concept and feed efficiency is an average concept. The marginal productivities have been computed on the basis of proportional increases in corn and soybean meal inputs.

Experiment 6323 The total gains beyond 50 pounds body weight for the incremental inputs of feed from 50 to 700 pounds are listed in Table 37. Table 38 contains the marginal productivities resulting from the incremental feed inputs. Both tables, as well as succeeding tables, are based on the eleven protein levels from 10 to 20 percent. Some of the values have been deleted from the tables since they would have represented larger gains than those included in the range of the data. Therefore, extrapolation beyond the range of the data has been virtually eliminated.

The table of total gains reflects a shift in the nutrient requirements as the pig increased in weight. The initial feed input of 50 pounds produced the largest gain on a 20 percent protein level. However, the two subsequent 50 pound feed inputs resulted in greater gains on the 19 and 18 percent protein levels, respectively. The feed inputs between 150 and 400 pounds produced the highest gains on 17 percent protein. Finally, the 16 percent protein level contributed the largest gains per pound of feed between 350 and 600 pounds. Thus, the requirement for protein declined in relation to the requirement for carbohydrates. Initially, all other rations were lagging the 20 percent protein ration in producing gain. However, the extreme protein levels required more time per unit of output than the intermediate protein levels in producing gains which approached market weight. The 10 percent protein level required the largest feed input to produce the desired gain over the production period.

The table of marginal productivities reflects the change in nutrient requirements more noticeably. The marginal productivity is highest at 20 percent protein for the initial 50 pound feed input. However, the highest marginal productivities for subsequent feed inputs were found at approximately one to two protein percentage units less than was noted for total gain. Therefore, the shift in nutrient requirements from protein to carbohydrates was actually affected at lower feed inputs than those reflected in the table of total gains. The marginal productivities for the lower protein levels of 10 to 14 percent were actually increased by the first 100 pounds of feed input. The only explanation which might be offered is that the stress of a change in environment was more easily surmounted by the pigs on protein levels which approximated their requirement. They reached the maximum peak in marginal gain on the first 50 pound feed input. However, once the pigs on the lower protein levels overcame the initial stress, they attained the maximum in marginal gain on the second 50 pound feed input. The marginal productivities for all other feed inputs and protein levels reflect decreasing gain for each added pound of feed.

The marginal productivity of feed over gain intervals may be found in Table 39. These marginal productivities are merely reflections of those listed for feed inputs since they represent the values determined for increasing amounts of body weight. Therefore, the shift in nutrient requirements is also evident in this table. A 20 percent protein level produced the highest productivity during the first interval while the 18 percent protein level was required to do so during the second interval. Protein levels of 16 and 15 percent resulted in the highest productivities for the 35 to 100 and 100 to 155 pound intervals, respectively. Marginal productivity was increased at protein levels of 10 to 16 percent for the first 35 pounds of gain, resembling the situation which existed for increasing feed inputs. However, the marginal productivities for all other gain intervals and protein levels reflected decreasing gain for each added pound of feed.

Experiment 6335 The total gains beyond 50 pounds of body weight for the incremental feed inputs are listed in Table 40. Table 41 contains the marginal productivities of each feed input.

The nutrient requirement shift accompanying increasing weight is reflected by the table of total gains in a manner similar to that in the previous experiment. However, the shift was accomplished at larger feed inputs than in the summer experiment. The first and second 50 pound feed inputs produced the largest gains on a 20 percent protein level. The third 50 pound input resulted in the highest gain on 19 percent protein, whereas the 18 percent level produced higher gains for the fourth and fifth feed inputs. Fifty pound feed inputs between 250 and 450 pounds exhibited the largest gains on the 17 percent ration. The largest response for the final 150 pounds of feed input was noted at 16 percent protein.

Once again, the nutrient requirement shift is more accurately reflected in the table of marginal productivities. The protein levels producing the highest marginal productivities were from one to three percentage units lower than those producing the highest gains for all feed inputs beyond the first 50 pounds. The trend in the nutrient shift reflected in the marginal productivities corresponds closely with that noted in the previous experiment. Again, the marginal productivities for the 10 to 14 percent protein levels increased for the first 100 pounds of feed input. With this exception, the data show that the marginal productivity of feed declined with increasing input.

The marginal productivities of feed over gain intervals are presented in Table 42. The shift in nutrient requirements which occurred in this experiment is similar to that noted in the previous trial. The protein level resulting in the highest productivity shifted from 20 to 19, 17, and 16 percent over the first four intervals and was constant at 15 percent for the remaining three intervals. Marginal productivity was increased at protein levels of 10 to 15 percent for the first 35 pounds of gain in this trial. However, the remaining data show that marginal productivity of feed declined with increasing input over gain intervals.

<u>Summary</u> A definite shift in the proportions of corn and soybean meal which maximized marginal feed productivities for the incremental feed inputs and over the gain intervals was observed in both trials. Similar observations were noted for the proportions of corn and soybean meal producing the

largest gains. With the exceptions noted, the data show that the marginal productivity of feed declined with increasing feed input and with increasing output of gain. The results of these data are in agreement with those determined by Woodworth (1954) and McKee (1955), concerning the decline in marginal productivity for increasing feed inputs. Woodworth (1954) illustrated a shift in nutrient requirements resulting from increasing inputs of feed, using a square root function. Similar results were also noted by McKee (1955), utilizing a quadratic function.

Marginal Rates of Substitution

The substitution rate is the amount of soybean meal which must be added to the ration to replace one pound of corn. Thus, the slope of the gain contour represents the rate at which soybean meal replaces corn in the ration at a specified level of gain. The curvature of the contours in Figure 18 indicates the change in the slope or, *i.e.*, the change in the substitution rate. Furthermore, the rate at which soybean meal replaces corn in a ration of a given protein level for varying weights of pigs is represented by the slope of the tangent to the contour at the point of intersection with the ration lines. The shift in each contour relative to the previous contour in Figure 18 indicates the change in the slope of the tangent or, in other words, in the substitution rate.

A diminishing rate of substitution is inherent in the convexity of the contours to the origin. That is, the rate at which soybean meal replaces corn diminishes as the ratio of soybean meal to corn in the ration is increased.

The substitution rate was computed as the ratio of the marginal physical product of soybean meal to that of corn. The marginal physical productivities were determined by computing the partial derivatives of the production functions (with respect to corn and soybean meal).

Substitution rates at gain contours

The rates of substitution of soybean meal for corn have been determined at the points where the eleven ration lines intersect the gain contours. Quantities of corn and soybean meal required to produce the gain specified at the gain contours have also been derived for the eleven rations. These data are illustrated for the two individual experiments as well as for the combined data in Tables 43, 44 and 45. The substitution rates and quantities of corn and soybean meal were all derived from the square root equations, 1.1, 1.3 and 1.5, corresponding to the individual and combined data.

The data illustrate the many combinations of corn and soybean meal which produced equal amounts of gain for seven different weights of pigs. For example, either 391.7 pounds of corn and 14.6 pounds of soybean meal or 226.1 pounds of corn and 85.7 pounds of soybean meal resulted in 100 pounds of gain in Experiment 6323. These rations account for a range in protein levels of 10 to 20 percent. Similarly, the data show the amounts of corn and soybean meal which produced a specified gain for a given level of protein. Whereas 75 pounds of gain were produced with 183.8 pounds of corn and 40.1 pounds of soybean meal at a level of 16 percent protein, 442.4 pounds of corn and 96.5 pounds of soybean meal were required to produce 155 pounds of gain at the same protein level (Experiment 6335).

Experiment 6323   The following equation was used to calculate the substitution rates (Table 43):

$$(2.1) \quad S = -\frac{-1.322398 + 4.30691/\sqrt{S} + .655558(\sqrt{C}/\sqrt{S})}{.129284 + 1.55179/\sqrt{C} + .655558(\sqrt{S}/\sqrt{C})}$$

The substitution rates are of diminishing marginal nature, as was indicated previously. Each added pound of soybean meal substitutes for a lesser amount of corn than the previous pound at a specified level of gain. Stated in an equivalent manner, the substitution rates decreased as the level of protein was increased in the ration. This property is to be expected since the percent protein of soybean meal is approximately six times that of corn. As the protein level is increased in the ration, it is shifted away from the percent protein of corn relative to that of soybean meal. Therefore, a pound of soybean meal has less value in replacing a pound of corn as the protein level in the ration is increased.

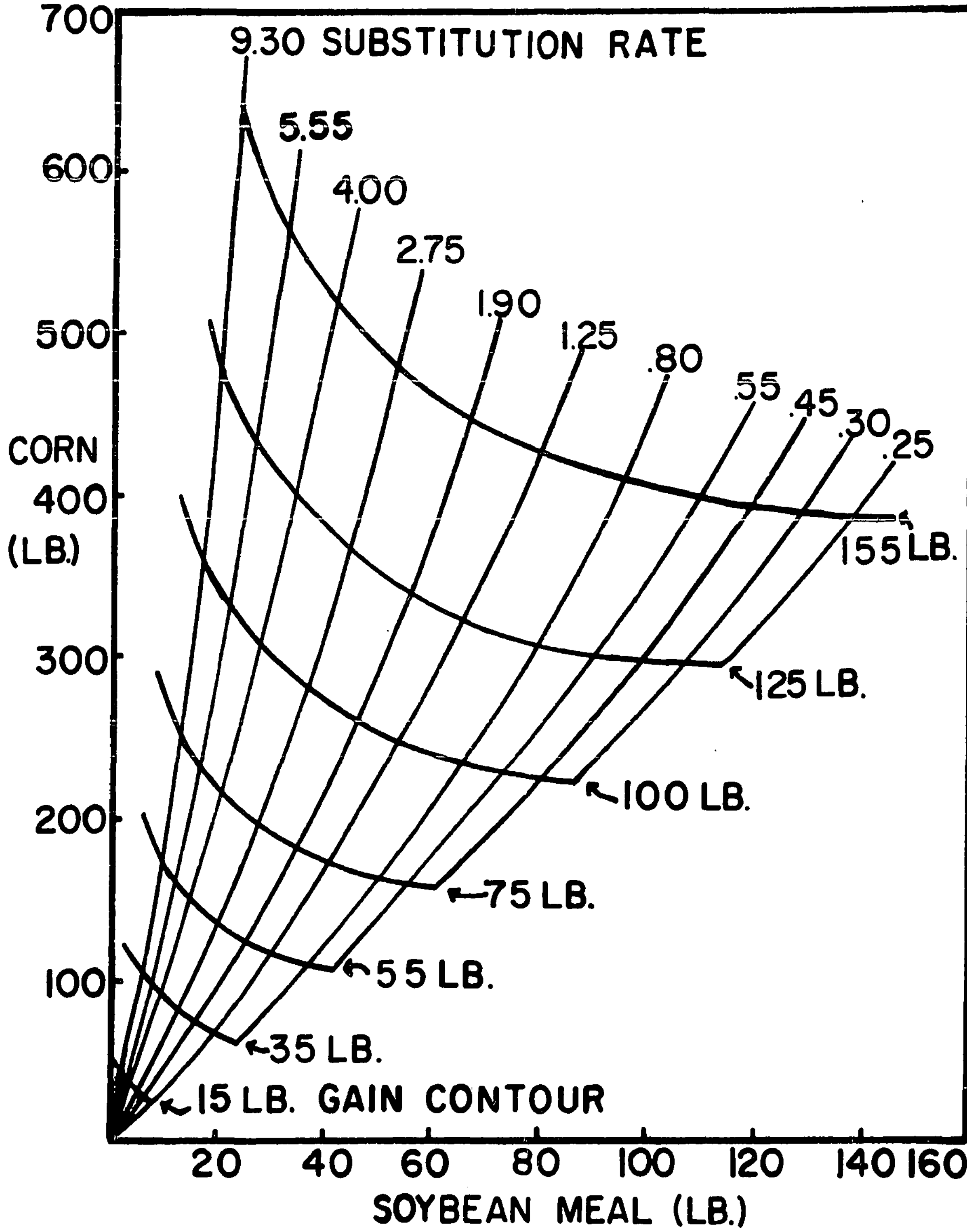
In addition, the substitution rates decreased at a given protein level as the pigs increased in body weight. Although the marginal productivities were declining, the marginal productivity of corn was decreasing less rapidly than that of soybean meal. Therefore, the marginal rate of substitution decreased as larger quantities of each component were consumed. This property implies that more carbohydrates are required in relation to protein at heavier weights.

The effect is illustrated by the curvature of the isoclines in Figure 19. An isocline joins the points on successive gain contours having the same substitution rate. The isoclines start at the origin, are convex to the soybean axis and curve toward the corn axis as the amount of gain is increased. Since the ration lines begin at the origin and are straight lines, it is obvious that the isoclines must cross ration lines of successively lower protein levels. As a result, a given protein level (ration line) exhibits decreasing substitution rates as it is projected over successively larger amounts of gain.

The only exception was noted at the 75 pound gain contour where the substitution rates increased for the 10 and 11 percent protein levels. This effect was probably due to the fact that the added amounts of minerals and vitamins were reduced at that point and replaced by an equivalent amount of corn.

Experiment 6335 The following equation was used to calculate the substitution rates (Table 44):

Figure 19. Experiment 6323 - isoclines which illustrate constant marginal rates of substitution of soybean meal for corn throughout the production period


9.30 SUBSTITUTION RATE
5.55
4.00
2.75
1.90
1.25
.80
.55
.45
.30
.25
155 LB.
125 LB.
100 LB.
75 LB.
55 LB.
35 LB.
15 LB. GAIN CONTOUR
CORN (LB.)
700
600
500
400
300
200
100
20
40
60
80
100
120
140
160
SOYBEAN MEAL (LB.)

$$(2.2) \quad S = -\frac{-1.271406 + 5.61018/\sqrt{S} + .548823(\sqrt{C}/\sqrt{S})}{.164316 + 1.16744/\sqrt{C} + .548823(\sqrt{S}/\sqrt{C})}$$

Properties of the substitution rates in this experiment were similar to those in the previous trial. The substitution rates decreased as the level of protein in the ration was increased for a specified level of gain. Similarly, the substitution rates decreased at a given protein level as the pigs increased in body weight. The exception was noted in this experiment at the 75 pound gain contour where the substitution rate increased only for the 10 percent level of protein. This effect may be explained in the same manner as was the effect in the previous experiment.

Substitution rates for the 10 percent protein level in this trial were higher for the first three contours and lower for the remaining four contours than those in the previous trial. The substitution rates for 20 percent protein in this trial were higher than those in the previous trial through all but the last two contours. This may indicate that the pigs at heavier weights placed a greater value on corn relative to the value of soybean meal during the winter trial. These relationships may be examined by comparing the relative shifts of the contours in Figure 18.

Combined data The following equation[1] was used to

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[1]Remember that the equation is the ratio of the partial derivatives of the production function with respect to corn and soybean meal.

calculate the substitution rates (Table 45):

$$(2.3)\quad S = -\frac{-1.464318 + 5.73391/\sqrt{S} + .617246(\sqrt{C}/\sqrt{S})}{.13158 + 1.4689/\sqrt{C} + .617246(\sqrt{S}/\sqrt{C})}$$

The substitution rates for the combined data displayed properties which were similar to those of the individual trials. All substitution rates for every protein level at each gain contour were comparable to the substitution rates in the two experiments. The increasing substitution rate for 10 percent protein at the 75 pound contour was merely a reflection of the same effect in the individual trials.

Woodworth (1954) obtained substitution rates of similar magnitude and with similar properties from a square root function in an equivalent study.

Substitution rates over gain intervals

Interpretation of the substitution rates presented in the previous tables may create minor difficulties in adaptation for the producer.

First, the substitution rates express the rate at which soybean meal replaces corn in the ration at each gain contour. Each contour was derived with reference to the initial body weight. As such, they reflect the total quantities which are consumed between 50 pounds initial body weight and the weight at the specified contour. Thus, the quantities of corn and soybean meal specified at a point on a given contour were consumed in the same proportion over that period. The substitution rates are derived from the same combinations of corn and soybean meal consumed during the period and, therefore, they are approximate averages over the period (Woodworth, 1954; McKee, 1955).

Second, the producer wishes to know which set of substitution rates to use when his animals are at weights in between those at the specified contours. He may also wish to know what quantities of corn and soybean meal are required to produce a change in weight between contours.

Therefore, the corn and soybean meal quantities required to produce gains over the gain intervals were calculated by subtraction of the quantities required to produce gains at adjacent contours. Substitution rates were calculated as averages over the gain intervals on the ration lines using the following formula described by Woodworth (1954):

$$(2.4) \quad S = - \frac{C_E - C_B + d_E S_E - d_B S_B}{S_E - S_B + (C_E/d_E) - (C_B/d_B)}$$

Quantities of corn and soybean meal at the beginning (B) and end (E) of each interval are represented by C and S. The substitution rates derived at each contour are represented by d.

<u>Summary</u> Corn and soybean meal quantities and substitution rates which were determined over gain intervals in the individual and combined sets of data are presented in Tables 46, 47 and 48.

The substitution rates presented in these tables reveal the same properties as those determined at the gain contours. Decreasing substitution rates resulted for all of the sets of data as the level of protein was increased over a given gain interval. Similarly, the rate of substitution decreased at a given protein level as the pigs increased in weight. However, the substitution rates increased over the 55 to 75 pound interval for lower protein levels in a manner similar to the effect which occurred at the 75 pound gain contour. The rates were increased for the 10 to 14 percent protein levels in experiment 6323 and for 10 to 12 percent protein in the second trial and the combined data. This effect was merely a reflection of the effect noted at the gain contour and therefore deserves the same explanation.

Substitution rates for 10 percent protein in Experiment 6335 (winter) were higher during the first and second intervals, but lower for the remaining five intervals than those in the summer trial. At the other extreme, the rates for 20 percent protein in the winter trial were higher than those in the summer trial over all but the last two intervals. This may indicate that the pigs at heavier weights placed a greater value on corn relative to that of soybean meal during the winter trial. Increased requirements of energy for maintenance in the winter may have caused this effect. Again, one may evaluate this by comparing the relationship of the intervals between contours in Figure 18.

The substitution rates estimated from the combined data were approximately equivalent to those derived from the individual experiments. For the most part, the substitution rates derived over gain intervals are lower in value than those obtained at the gain contours. This is expected since the latter substitution rates approximate the average over the period from the initial body weight to the gain contour.

Cost Minimization of Feed

The prime goal in a swine feeding enterprise is usually maximization of profit. Minimization of the costs of the enterprise is one method by which this goal may be achieved. Since the cost of the ration accounts for a major portion of the costs of the enterprise, it is important that feed costs be minimized.

The costs of corn and soybean meal consumed in producing a unit of gain are minimized by equating the substitution rate of soybean meal for corn to the soybean meal/corn price ratio. This condition for minimizing feed costs may be illustrated by the following algebraic equation where MPP represents the marginal physical product, P represents price, and C and S represent corn and soybean meal, respectively:

$$(2.5) \qquad -\frac{MPP(C)}{MPP(S)} = \frac{P(S)}{P(C)}$$

For example, it may be assumed that a substitution rate of 3.6 exists for a particular ration which is being fed. One may further assume that the prices of corn and soybean meal are 2¢ and 6¢ per pound, respectively. One pound of soybean meal costing 6¢ will replace 3.6 pounds of corn costing 7.2¢. It is obvious that feed costs may be reduced by substituting one pound of soybean meal for 3.6 pounds of corn.

Changing the composition of the ration by replacing some of the corn with soybean meal will alter the substitution rate. Continuing with the previous example, the substitution rate in the ration presently being fed may be 3.4. Since one pound of soybean meal costing 6¢ will replace 3.4 pounds of corn costing 6.8¢, the cost of the ration may again be reduced by making the substitution. This practice would be continued until the substitution rate equalled the price ratio of 3.0. Feed costs cannot be reduced once the substitution rate of 3.0 is attained, since one pound of soybean meal costing 6¢ will then replace three pounds of corn, also costing 6¢. Any additional replacement of one ingredient with the other would result in a costlier ration as long as the price ratio remained fixed.

The problem of minimizing feed costs may be simplified by initially selecting a ration which has a substitution rate equal to the price ratio.

An extension of this situation may serve to illustrate another application of the use of substitution rates in minimization of feed costs. Suppose the price of soybean meal is increased to 6.6¢ per pound. The price ratio is now 3.3. However, the substitution rate in the ration now being fed is

3.0. Thus, the cost of the ration may be reduced by replacing one pound of soybean meal costing 6.6¢ with three pounds of corn at a cost of 6¢. The substitution rate in the new ration would be different than the corresponding substitution rate in the previous ration. Therefore, one must continue replacing soybean meal with corn, the relatively cheaper ingredient, until the substitution rate is equal to the price ratio. More simply, the ration corresponding to the substitution rate of 3.3 would initially be selected.

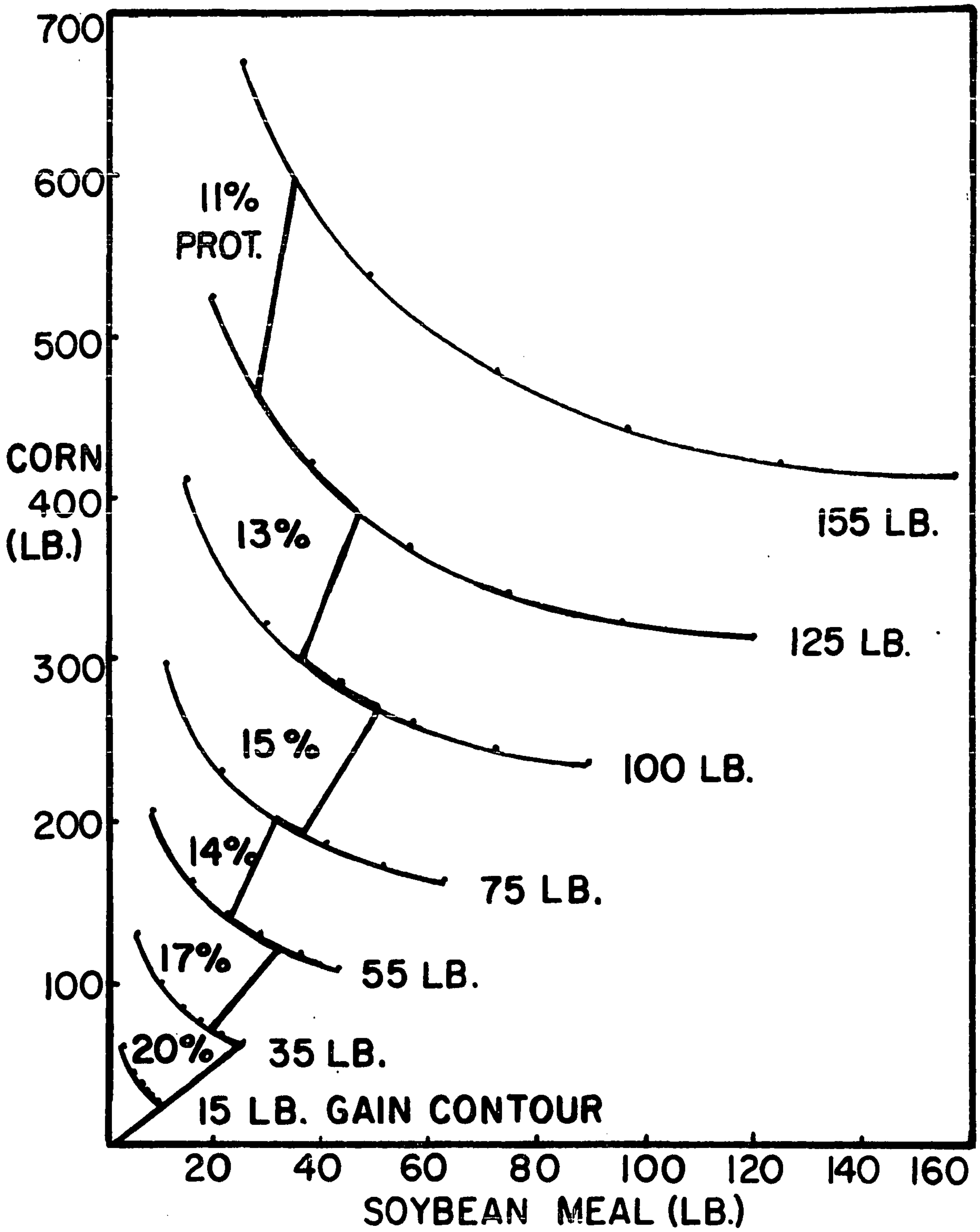
In practice, a producer changes the ration once or twice during the production period by reducing the level of protein. This procedure is usually followed to insure maximum gain and efficient utilization of feed. However, this practice does not insure minimum cost of the ration. The preferable alternative of feeding one ration throughout the production period might be followed. The ration would be based on the prices of corn and soybean meal and on the substitution rate at the heaviest gain contour. The level of protein would remain constant over the production period. Any other constant proportion of corn and soybean meal which might be fed over the entire production period would be costlier. The ration may or may not be cheaper than the practice of feeding for maximum rate and efficiency of gain, depending on the changes in the relative costs of corn and soybean meal during the production period.

Feeding a fixed proportion of corn and soybean meal during the entire period will not result in minimum feed costs when the substitution rate changes as the pig changes in weight. Additional reduction in the cost of the ration may be accomplished by more frequent changes in the proportions of corn and soybean meal. Therefore, a second alternative would be to change the proportions of corn and soybean meal in the ration for every small unit of gain which might be produced. However, it would not be practical to change the ration daily for the production of every pound or two of gain. The saving in feed cost would probably be negated by the alternative cost of the time required to affect such a change. A more acceptable method might involve changing the ration every two weeks. Thus, the production period represented in the study reported herein has been divided into quantities of gain which might be expected over every two week interval.

The process of minimization of feed costs over the production period is illustrated in Figure 20. The gain contours in the illustration were determined in Experiment 6335. The substitution rates and corn and soybean meal quantities which will be discussed pertain to those calculated for gain intervals (Table 47).

Suppose the prices of corn and soybean meal are 2¢ and 3.76¢ per pound, respectively. In addition, assume that the initial weight of the pig is 50 pounds. Equating the price ratio of 1.88 to the same substitution rate results in the use of a ration containing 20 percent protein. The initial 15 pounds of gain will be produced by feeding 25.5 pounds of corn

Figure 20. Experiment 6335 - expansion path of the least cost ration corresponding to price changes of corn and soybean meal during the production period



700
600
500
400
300
200
100
CORN (LB.)
11% PROT.
13%
15%
14%
17%
20%
155 LB.
125 LB.
100 LB.
75 LB.
55 LB.
35 LB.
15 LB. GAIN CONTOUR
20
40
60
80
100
120
140
160
SOYBEAN MEAL (LB.)

and 9.9 pounds of soybean meal. Next, the price of corn is increased to 2.4¢ per pound and the price of soybean meal is decreased to 2.47¢ per pound. The price ratio or substitution rate of 1.03 indicates that a 20 percent protein ration must again be fed over the second interval (15 to 35 pounds). Although the price ratio has changed, the corresponding substitution rate for the heavier pig happens to exist at the 20 percent protein level. This is an illustration of the decrease in the substitution rate as the weight of the pig is increased.

Now, suppose that the price of soybean meal increased to 2.88¢ per pound while the price of corn remained constant at 2.4¢ per pound. It would not be profitable to feed according to the old substitution rate of 1.03 since 1.03 pounds of corn costing 2.47¢ will replace one pound of soybean meal costing 2.88¢. Therefore, soybean meal must be replaced in the ration by corn, the relatively cheaper ingredient. The price ratio or substitution rate of 1.2 indicates that a 17 percent protein level must be fed over the interval from 35 to 55 pounds.

If the price of soybean meal next increased to 5.23¢ per pound while the price of corn remained at 2.4¢, the cost of the ration would again be reduced by substituting corn for soybean meal. The price ratio of 2.18 will require the feeding of a 14 percent protein ration over the 55 to 75 pound interval.

Finally, suppose that the price of soybean meal decreased to 4.08¢ per pound while the price of corn increased to 3¢ per pound. The cost of the ration will now be reduced by substituting one pound of soybean meal at a cost of 4.08¢ for 2.18 pounds of corn at a cost of 6.54¢. Thus, soybean meal is the relatively cheaper ingredient. The price ratio or substitution rate of 1.36 indicates that 78.5 pounds of corn and 14.4 pounds of soybean meal are required to produce the gain over the interval from 75 to 100 pounds. The protein level in the ration is 15 percent compared to the previous level of 14 percent.

The path of the minimum cost ration resulting from additional price changes in corn and/or soybean meal is illustrated in Figure 20.

Ham and Loin Functions

Feed costs may be minimized as a method of increasing the profit margin in a swine enterprise. Minimization of the costs of the inputs of protein and energy sources is accomplished by utilizing the relative substitution properties of the inputs over intervals during the production period. Although the cost of the ration may be minimized with respect to the costs of the inputs, the effect of the combination of inputs on the quality of the final product must be considered.

A substantial share of the business transacted in the swine market is based on carcass quality and the incidence of this will likely be increased in the future. The percent ham and loin of the carcass is considered to be a reasonably effective predictor of the carcass quality of the pig. Thus, it is important that the producer consider the effect of a change in the components of the ration on carcass quality, for example, on percent ham and loin.

The carcass quality of the pig may vary markedly with changes in the level of protein in the ration. Specifically, an increase (decrease) in the protein level may affect a corresponding increase (decrease) in the percent ham and loin of the carcass. A price change of sufficient magnitude to cause a large shift in the proportions of corn and soybean meal will cause a wide variation in the percent protein of the ration. Therefore, one must be able to predict the effect of a change in the combination of corn and soybean meal in the ration on the percent ham and loin of the carcass.

Several functions have been examined as alternatives for expressing the relationship between the inputs of corn (C) and soybean meal (S) and the resulting percent ham and loin (HL) of the carcass. Each function has been fitted to the observations from all six rations in each of the individual and combined sets of data. The level of protein is therefore implicit in the combinations of corn and soybean meal constituting the observations. The observations used in estimating the functions consisted of the total inputs of corn and soybean meal corresponding to the percent ham and loin determined at market weight.

Two of the functions are linear with one containing a crossproduct term which permits the expression of an interaction between corn and soybean meal. The following four functions are modified forms of the quadratic: (1) a quadratic without an interaction term, (2) a square root without an interaction term, (3) a quadratic with the squared exponents of the second power terms replaced by an exponent of 1.5, also without an interaction term and (4) a quadratic ratio, containing an interaction term which expresses the ratio between the inputs of soybean meal and corn.

The quadratic 1.5 power function is a compromise between the quadratic and the square root, which declines less rapidly than the quadratic at higher protein levels. The quadratics, with the exception of the quadratic ratio, originally included the interaction term. However, an extremely high correlation between the second power term for soybean meal and the interaction term necessitated deletion of the interaction term from the functions in order to avoid computational difficulties. The inclusion of a variable which was so highly correlated with another variable would not have improved the estimation of the function.

Estimated functions

Experiment 6323 The following equations were fitted to the observations, using regression analysis:

(3.1) $HL = 43.602250 - .013895C - .004063S$

(3.2) $HL = 43.010090 - .012149C + .021299S - .00006520CS$

(3.3) $HL = 54.616386 - .059653C + .004966S + .00004546C^2 - .00006748S^2$

$$(3.4)\quad HL = 88.697623 + .087547C - .045261S - 4.427250\sqrt{C} + .720940\sqrt{S}\ .$$

$$(3.5)\quad HL = 58.018646 - .106288C + .023373S + .00276971C^{1.5} - .00213934S^{1.5}$$

$$(3.6)\quad HL = 67.443350 - .103641C + .033555S + .00008325C^{2} + .00002725S^{2} - 20.2979(S/C)$$

The analysis of variance plan and observed mean squares for the functions are contained in Table 49. Correlation coefficients, and standard errors and significance tests of the regression coefficients are listed in Table 50. Table 55 contains the probability levels pertaining to significance of the regression coefficients.

All of the functions expressed highly significant regressions of ham and loin percent on corn and soybean meal combinations (protein level).

The square root function accounted for the most variation in ham and loin percent, .5415, compared to the linear function which accounted for the least amount of variation, .5025. The functions appear to account for little more than one-half of the variation. However, actual observations taken at a given protein level indicated that the percent ham and loin of the carcass was quite variable. One may note that the multiple correlation coefficients appear to be reasonable estimates of the relation between ham and loin percent and corn and soybean meal combinations (i.e., level of protein).

For example, the square root function expresses a correlation coefficient of .7359.

In general, the regression coefficients for the corn terms were significant at a probability of .40 or less whereas the regression coefficients for soybean meal were not. Only those coefficients of the soybean meal terms in the square root function were significant at a probability of .50 or less. The probability levels ranged from .01 or less to .40 or less for the significance of the regression coefficients for corn in the various functions.

Experiment 6335 Following are the estimated equations:

$$(4.1)\quad HL = 42.169633 - .009505C + .007126S$$

$$(4.2)\quad HL = 43.217193 - .011923C - .019759S + .00006180CS$$

$$(4.3)\quad HL = 36.942756 + .003462C + .031947S - .00000923C^2 - .00010768S^2$$

$$(4.4)\quad HL = 37.413390 - .004364C - .029129S - .058700\sqrt{C} + .744308\sqrt{S}$$

$$(4.5)\quad HL = 37.006940 + .005911C + .052834S - .000347820C^{1.5} - 00287896S^{1.5}$$

$$(4.6)\quad HL = 15.548987 + .075833C - .012738S - .00007021C^2 - .00018728S^2 + 28.8290(S/C)$$

The analysis of variance plan and observed mean squares for the functions are presented in Table 51. Correlation coefficients, and standard errors and significance tests of the regression coefficients are listed in Table 52. Table 55 contains the probability levels pertaining to significance of the regression coefficients.

Highly significant regressions of ham and loin percent on corn and soybean meal combinations (protein level) were expressed by all of the functions.

The linear function again accounted for the least amount of variation in ham and loin percent, .6578. However, the quadratic ratio accounted for slightly more of the variation in ham and loin percent, .6904, compared to .6869 for the square root function. The multiple correlations between percent ham and loin and corn and soybean meal combinations (protein level) were higher in this trial than in the previous trial. The square root and quadratic ratio functions displayed multiple correlations of .8288 and .8309, respectively.

Contrary to the previous trial, the regression coefficients for soybean meal in the quadratic equations were significant at probabilities of .40 or less whereas those for corn were not. However, the linear functions constituted exceptions in which the coefficients for corn were of greater significance than those for soybean meal.

<u>Combined data</u> The following equations estimated the relationship between ham and loin percent and corn and soybean meal combinations (protein level):

(5.1) $HL = 37.598965 - .002955C + .015013S$

(5.2) $HL = 40.027360 - .008351C - .037019S + .00012065CS$

(5.3) $HL = 28.728561 + .025624C + .040611S - .00002520C^2 - .00011541S^2$

$$(5.4)\quad HL = 19.844933 - .020246C - .035517S + .979330\sqrt{C} + 1.012005\sqrt{S}$$

$$(5.5)\quad HL = 27.368095 + .043171C + .066984S - .00126491C^{1.5} - .00334272S^{1.5}$$

$$(5.6)\quad HL = 45.175515 - .031224C + .077947S + .00002363C^{2} - .00004299S^{2} - 23.5225(S/C)$$

Table 53 presents the analysis of variance plan and observed mean squares for the functions. Correlation coefficients, and standard errors and significance tests of the regression coefficients are listed in Table 54. The probability levels of significance of the regression coefficients are displayed in Table 55.

All of the functions again expressed highly significant regressions of ham and loin percent on corn and soybean meal combinations (protein level).

The least amount of variation, (.3881), was explained by the linear function while the square root function again explained a greater proportion of the variation (.4373) in the dependent variable. All of the functions explained a lesser proportion of the variation in the combined data than in either of the individual trials. The multiple correlations between the dependent and independent variables, ranging from .6230 to .6613, were lower than those in the individual experiments. It is apparent that a substantial amount of variation exists in the ham and loin percent at a given protein level for the combined data.

The regression coefficients for corn were significant at probabilities ranging from .05 or less to .50 or less. Probability levels of .01 or less to .40 or less indicated significance for the regression coefficients of the soybean meal terms.

Predicted ham and loin percent

The ham and loin functions estimated from the data may be utilized to predict the percent ham and loin resulting from the total inputs of corn and soybean meal over the production period. The change in ham and loin percent resulting from a change in the combinations of corn and soybean meal (*i.e.*, protein level) may then be calculated. Since the change in ham and loin percent is a reflection of the change in value of the carcass, it is hoped that the producer will be able to balance this economic effect against the economic effect of the ration change.

Suppose, for example, that the prices of corn and soybean meal have changed from the previous level, requiring a new combination of the two inputs to minimize the cost of the ration. The differential in cost of the feed required over the interval from the present weight of the pig to market weight would be calculated for the two rations. Comparison of the saving in feed costs with the gain or loss in carcass value would provide the basis for deciding whether or not the ration change was economically justifiable.

An improvement could be made in this process by measuring the percent ham and loin of the carcass at each gain contour. Prediction of the ham and loin percent would provide the basis for calculation of the change in ham and loin percent for various protein levels over each interval. The economic value of the change in ham and loin percent could then be compared to the saving in feed cost over each interval. Although the amount of experimental material required for such a study would be tremendously large, it would appear that recommendation of the study would be justified.

However, it is known that there is little daily storage of protein. Thus, it seems reasonable to assume that the effect of a ration change during a given gain interval on the change in percent ham and loin at market weight would be essentially independent of a ration change during other gain intervals.

With these concepts in mind, predictions of ham and loin percent at market weight were made from the several functions for the eleven protein levels. The change in ham and loin percent between each protein level was then calculated. The absolute ham and loin percent as well as the change in the values were compared to the average of the experimental observations taken at each of the six protein levels.

Experiment 6323 The predicted values for ham and loin percent for the six functions are listed in Table 56. Table 57 shows the changes in percent ham and loin between each protein level.

While some variation exists among the several functions concerning prediction of the values, the data show that the predicted values are comparatively close to the observed values. However, the predictions appear to provide more accurate estimates of ham and loin percent at the lower protein levels. The square root function (without interaction) estimates values which are more comparable to the observed values than do any of the other functions.

Examination of the change in ham and loin percent reveals that there is a great deal of variation between the observed change and the changes estimated from the functions. Much of this variation may be due to the decrease in ham and loin percent at the 18 percent protein level. There is no readily apparent logic which may be offered for this effect. Nevertheless, the change in ham and loin percent as estimated by the functions follow a reasonable trend which might be expected. That is, one would expect a diminishing rate of increase in ham and loin percent with increasing protein level.

Experiment 6335 Table 58 presents the predicted values for percent ham and loin for the six functions. The changes in percent ham and loin between each protein level are listed in Table 59.

Comparison of the predicted values with the observed values illustrates that all of the functions have produced values which are reasonably accurate. The values for the lowest protein level have been underestimated somewhat. Also, the predicted values at the 18 percent protein level do not agree with those observed. However, the decrease in ham and loin percent at this protein level has created this disagreement and, again, is not readily explainable.

The changes in ham and loin percent predicted from the functions are in reasonable agreement with the changes in the observed values. The only exception is at 18 percent protein, due to the effect mentioned previously. The percent ham and loin was increased at a diminishing rate with increasing protein level, similar to the effect in the previous trial.

The ham and loin percent, as well as the change in the percent appear to have been predicted more accurately in this trial than in the previous trial.

Combined data The predicted values for ham and loin percent for the six functions are contained in Table 60. The changes in percent ham and loin between each protein level are displayed in Table 61.

All of the functions have predicted values which compare quite closely with the averages of the observed values for the two trials. The exception to this is at the 18 percent protein level and is merely a reflection of the effect discovered in the individual trials. The square root function provides closer estimates of the values from 10 to 16 percent protein than any of the other functions. The square root function also provides values comparable to the other functions for the remaining protein levels. The values predicted from the functions for the combined data appear to be more accurate than those predicted from the functions in each of the individual trials.

The changes in percent ham and loin predicted from the functions agree closely with the observed changes. Again, the exception is at the 18 percent protein level. However, the diminishing trend in the rate of increase in percent ham and loin with increasing protein level is comparable to what one would expect. The predicted changes in ham and loin percent also appear to be more accurate for the combined data than for the individual trials.

Choice of function

The basis for selection of the appropriate function must depend on many criteria. Nutritional logic is one criteria which may be utilized in selection of the function representing the relationship between percent ham and loin and combinations of corn and soybean meal. Previous experimental observations indicate that the function representing percent ham and loin is concave to the plane of the inputs of corn and soybean meal. In other words, the function is of the quadratic form over the range of combinations of corn and soybean meal which represent increasing protein level. This may be verified by examining the results of the ham and loin regression analysis in the sections concerning the individual experiments in this text.

Thus, the linear functions would be eliminated from consideration.

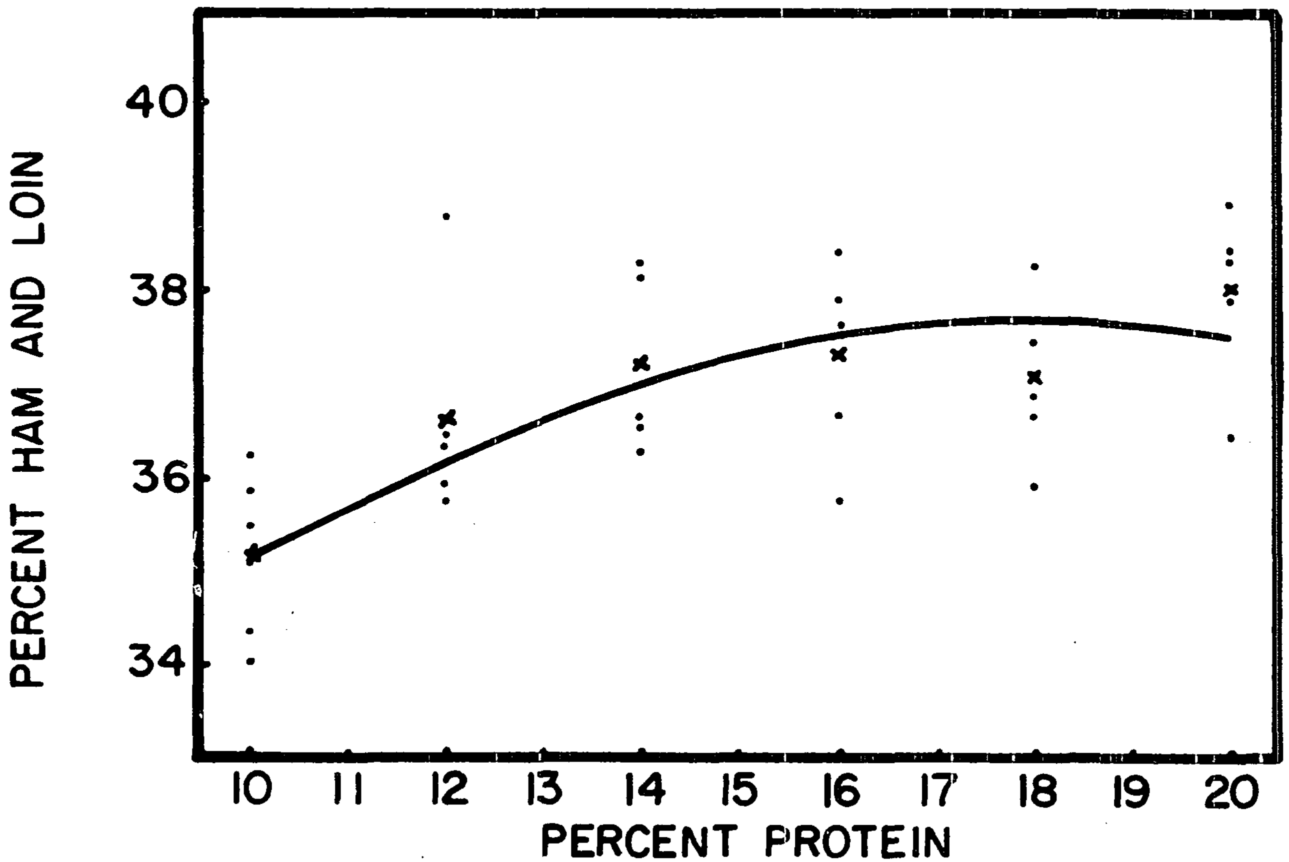
Examination of the predicted values for ham and loin percent indicates that the square root function (without interaction) estimated most of the observed values more accurately than any of the other functions. The square root function also produced estimates of the changes in percent ham and loin which were comparable to those predicted by the remaining functions.

The square root function accounted for a greater proportion of variation in ham and loin percent than any other function in Experiment 6323 and for the combined data. Moreover, the square root function fitted the data in Experiment 6335 almost as closely as did the quadratic ratio, which accounted for the largest amount of variation in that trial.

Therefore, the square root function appears to be the appropriate function on the basis of accuracy of prediction and statistical evaluation.

The fit of the square root function to the eleven protein levels has been plotted against the experimental observations for 10, 12, 14, 16, 18 and 20 percent protein. Figures 21, 22 and 23 illustrate the plots of the square root function for the individual and combined sets of data. The averages of the experimental observations for each of the six protein levels have also been plotted in the figures for the purpose of comparison with the points estimated by the function. Some

Figure 21. Experiment 6323 - comparison of the average of the experimental observations (x) with the ham and loin percent predicted by the square root function (equation 3.4)



PERCENT HAM AND LOIN
40
38
36
34
10
11
12
13
14
15
16
17
18
19
20
PERCENT PROTEIN

Figure 22. Experiment 6335 - comparison of the average of the experimental observations (x) with the ham and loin percent predicted by the square root function (equation 4.4)

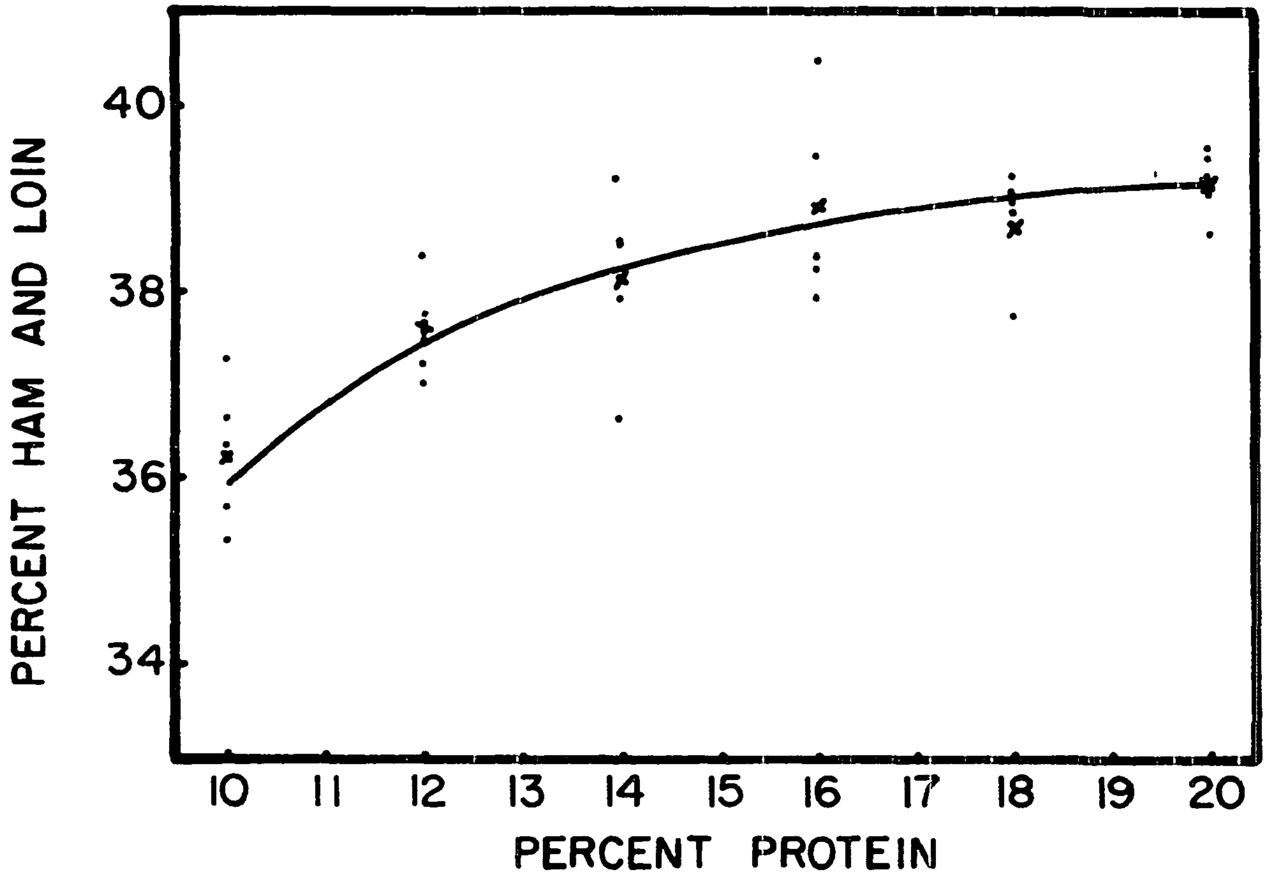
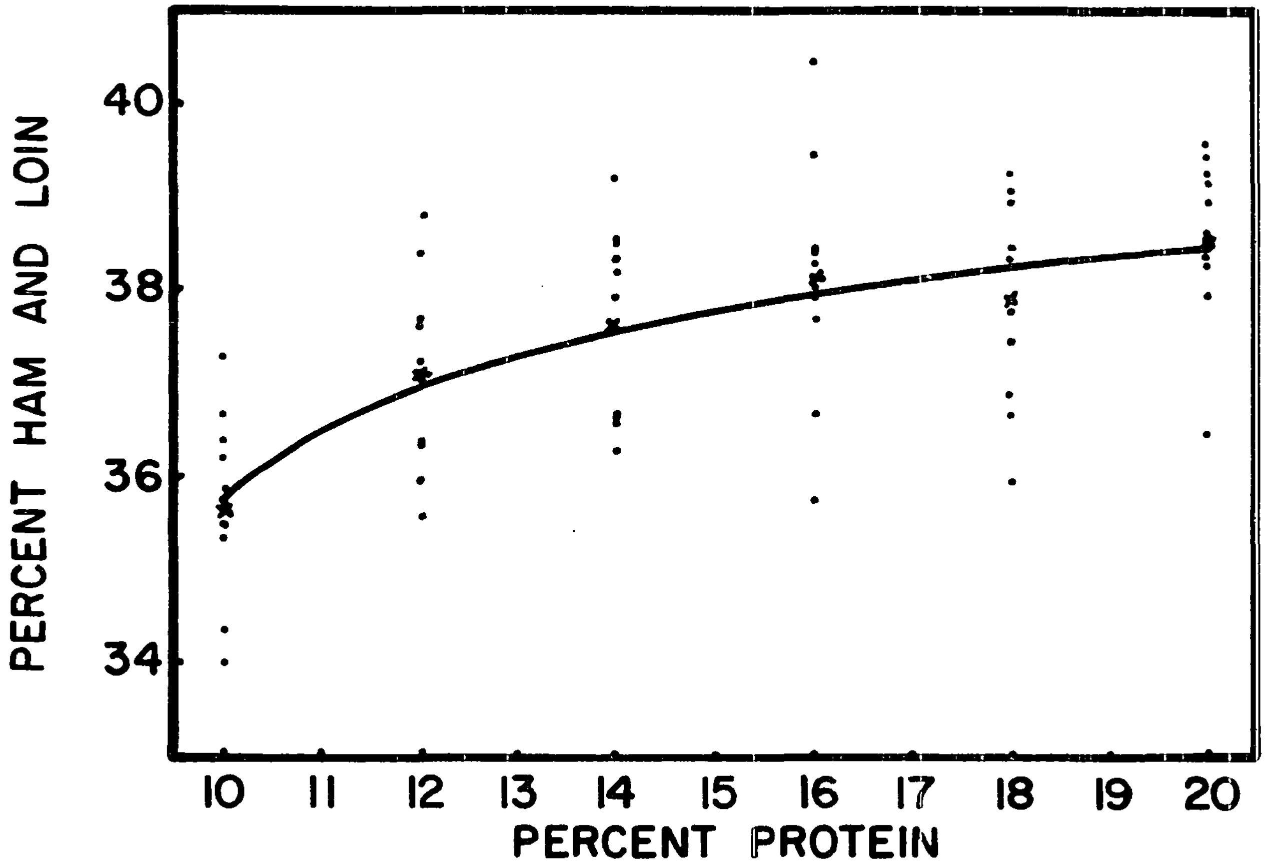

PERCENT HAM AND LOIN
40
38
36
34
10
11
12
13
14
15
16
17
18
19
20
PERCENT PROTEIN

Figure 23. Combined experiments 6323, 6335 - comparison of the average of the experimental observations (x) with the ham and loin percent predicted by the square root function (equation 5.4)


PERCENT HAM AND LOIN
40
38
36
34
10
11
12
13
14
15
16
17
18
19
20
PERCENT PROTEIN

variation exists between the averages and the estimated points in Experiment 6323 (Figure 21). However, the points estimated by the function agree quite closely with the averages in Experiment 6335 (Figure 22) and in the combined data (Figure 23).

Prediction of Time

Another important aspect of cost consideration in a swine enterprise is that of time. Feed costs will be minimized by the specific combination of corn and soybean meal for which the substitution rate corresponds to the price ratio of the two inputs. The specific combinations of corn and soybean meal may range from 10 to 20 percent in protein level. Variations in the combinations of the two inputs (*i.e.*, in protein level) will affect the rate of body weight gain of the pig. For example, the rate of gain of the pig on 10 percent protein is less rapid than on a protein level of 18 percent. The production period will be extended because of low daily gains. The selling price of the pig may either be increased or decreased depending on whether the low protein ration caused the pig to attain market weight during a high or low price period. Therefore, the producer must consider the effect of a change in the ration components on the time required by the pig to attain market weight.

Choice of function

Prediction of the time requirements over gain intervals constituted the primary interest in consideration of the effect of ration changes on time. Therefore, a marginal concept was utilized to estimate time over the intervals. Marginal days per pound of gain (MD) was expressed as a function of the percent protein (P) in the ration and the marginal gain (G) of the pig over each two week interval. This function accounted for the protein level as well as for the effect of differences in the weight of the pig due to the protein level.

The two types of functions which have been examined as alternatives for expressing this relationship are the quadratic and the square root. Each function was fitted to the observations from all six protein levels in the individual and combined sets of data.

Experiment 6323 The following functions were estimated using regression analysis:

$$(6.1)\quad MD = 6.823187 + .293266P + .007399G - 2.564365\sqrt{P} - .227324\sqrt{G} + .019684\sqrt{P}\sqrt{G}$$

$$(6.2)\quad MD = 2.548178 - .188361P - .009485G + .00515816P^2 + .00003125G^2 + .00017268PG$$

The analysis of variance plan and observed mean squares for the functions are contained in Table 62. Correlation coefficients, and standard errors and significance tests of the regression coefficients are also listed (Table 63).

Highly significant regressions of marginal days per pound of gain on percent protein and marginal gain were noted for both functions. All of the regression coefficients for each function were significant at a probability of .01 or less.

The square root function explained a greater proportion of the variation in time, .6451, in comparison to .6185 for the quadratic function.

Experiment 6335   The estimates for the two equations are as follows:

$$(6.3)\quad MD = 8.051227 + .342000P + .007450G - 3.042180\sqrt{P} - .302767\sqrt{G} + .036680\sqrt{P}\sqrt{G}$$

$$(6.4)\quad MD = 2.877232 - .215954P - .012258G + .00600086P^2 + .000036l9G^2 + .00026101PG$$

Table 64 contains the analysis of variance plan and observed mean squares for the functions. Correlation coefficients, and standard errors and significance tests of the regression coefficients are presented in Table 65.

The regression of marginal days per pound of gain on percent protein and marginal gain was highly significant for both functions. All of the regression coefficients for both functions were significant at a probability of .01 or less.

The square root function again accounted for a larger amount of the variation in time. The coefficients of determination for the square root and quadratic functions were .6634 and .6339, respectively.

Combined data   Following are the equations estimated by regression analysis:

$$(6.5)\quad MD = 7.477518 + .319399P + .007456G - 2.819025\sqrt{P} - .267026\sqrt{G} + .028451\sqrt{P}\sqrt{G}$$

$$(6.6)\quad MD = 2.722292 - .202937P - .010945G + .00560413P^2 + .00003395G^2 + .00021762PG$$

The analysis of variance plan and observed mean squares for the functions may be found in Table 66. Correlation coefficients, and standard errors and significance tests of the regression coefficients are contained in Table 67.

Regressions of marginal days per pound of gain on percent protein and marginal gain were highly significant for the two functions. The regression coefficients for both functions were significant at a probability of .01 or less.

A larger proportion of the variation in time was once again explained by the square root function. The coefficients of determination for the square root and quadratic functions were .6405 and .6130, respectively.

When both of the functions were plotted they indicated similar predictions of the time required to produce a given gain for a specified protein level. The choice of the appropriate function was dependent on comparison of the coefficients of determination. The square root function explained a larger proportion of the variation in time than did the quadratic. Therefore, the square root function appeared to be appropriate for expressing marginal time per pound of gain as a function of percent protein and marginal gain.

Time predictions

Marginal days per pound of gain were calculated at each gain contour for the eleven protein levels in the individual and combined sets of data. Estimates of the number of days required during each gain interval, as well as the number of days required to attain each gain contour were calculated from the values for marginal time.

Experiment 6323 Predictions of marginal days per pound of gain for each gain interval are contained in Table 68. Marginal time decreased for each protein level over the gain intervals from 15 to 100 pounds. However, marginal time increased for the 13 to 20 percent protein levels over the interval from 100 to 125 pounds and for all protein levels for the last 30 pounds of gain. The indication is that the rate of gain was plateauing at a body weight of 175 pounds. This effect is consistent with the nutritional observation that average daily gain increases very slowly after a body weight of 160 pounds is attained. Therefore, the marginal gain would nearly reach a plateau. The extreme protein levels required more time to produce an added pound of gain over all of the gain intervals than did the intermediate levels.

Similarly, the extreme protein levels required more days to produce a given amount of gain over each gain interval (Table 69). The path for the least time required to attain a given gain was traced over the production period. A protein level of 18 percent required the least amount of time over the first interval. The three equal gain intervals (20 pounds) from 15 to 75 pounds were produced in the least amount of time on 17 percent protein. The least time path then shifted to 16 percent for the intervals from 75 to 155 pounds. Thus, there was a shift in the nutrient requirement from protein toward carbohydrates for the heavier gain intervals. However, the estimates were so close that rounding of the numbers to the nearest day virtually eliminated this effect.

Examination of the number of days required over the production period indicated that the 15 percent protein level required the least number of days (Table 70). A 10 percent protein level required 36 more days to produce 155 pounds of gain than did the 15 percent protein level. A protein level of 20 percent required 6 more days than 15 percent protein. In other words, the extreme protein levels required more days to produce pigs of market weight than did the intermediate levels of protein. The least time path resulted from protein levels of 18 percent at the 15 and 35 pound gain contours. A protein level of 17 percent required the least amount of time to attain the gain specified by the remaining contours.

<u>Experiment 6335</u> Predictions of marginal days per pound of gain again resulted in a decrease in marginal time for each protein level over the gain intervals from 15 to 100 pounds (Table 71). However, in this trial the increase in marginal time over the interval from 100 to 125 pounds was noted for the 16 to 20 percent protein levels. All of the protein levels produced an increase in marginal days per added pound of gain for the last gain interval. The rate of gain plateaued in a

manner similar to that in the previous trial. The added days per added pound of gain were greater for the higher protein levels than for the corresponding lower levels of protein. Thus, the pig placed a higher value on lower levels of protein.

The extreme protein levels again required more time than the intermediate levels to produce a given gain over each gain interval (Table 72). The least time path in this trial was found at successively lower protein levels as the gain intervals corresponding to heavier weights were attained. The protein level consistent with the least time path decreased from 18 to 14 percent as the weight was increased. The 20 percent protein level required one more day than the protein level of 10 percent to produce the last 30 pounds of gain, indicating that a greater value was placed on the lower protein level by the pig.

The amount of time required over the entire production period was similar to the time required for all protein levels in the previous trial (Table 73). The extreme protein levels again required more days to produce 155 pounds of gain than did the intermediate levels. The least time path followed a higher protein level over the production period at the gain contours than was noted for the gain intervals in this trial.

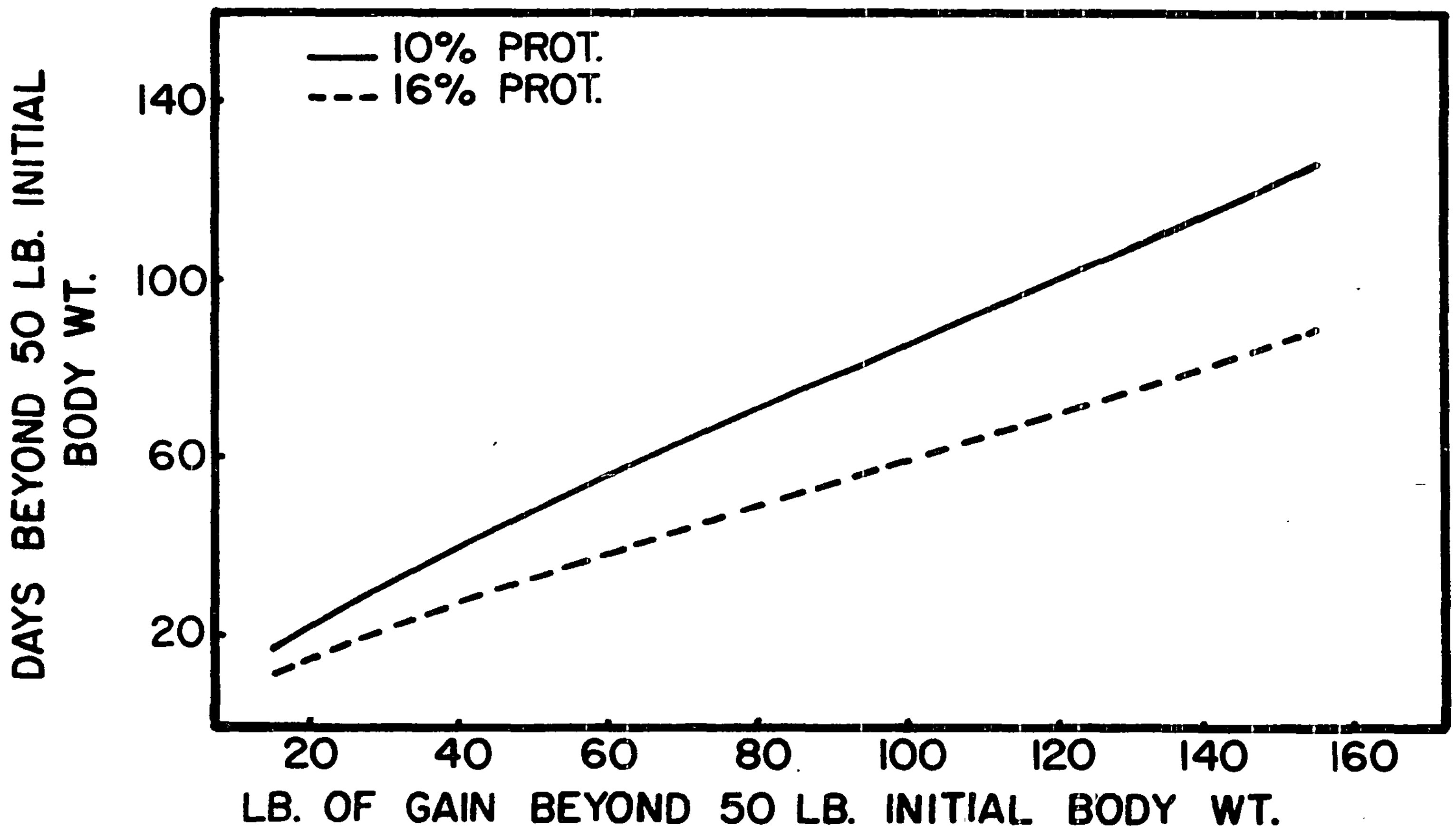
Combined data   The decrease in marginal days per marginal pound of gain noted for gain intervals in the combined data was similar to that noted in each trial (Table 74). The increase in marginal time for the interval from 100 to 125 pounds occurred at the 15 to 20 percent protein levels. Protein levels of 11 to 20 percent produced an increase in marginal time for the last 30 pounds of gain.

The extreme protein levels resulted in more time required to produce a given gain over each gain interval (Table 75). The protein level consistent with the least time path decreased from 18 to 15 percent as weight increased over the gain intervals.

The total number of days required over the entire production period approximated the average of the two individual trials (Table 76). The fewest number of days were required on a level of 16 percent protein. The lowest level of protein required 35 more days to produce 155 pounds of gain than the protein level corresponding to the least time path. The least time path followed a higher protein level over the production period at the gain contours than the path which corresponded to the gain intervals.

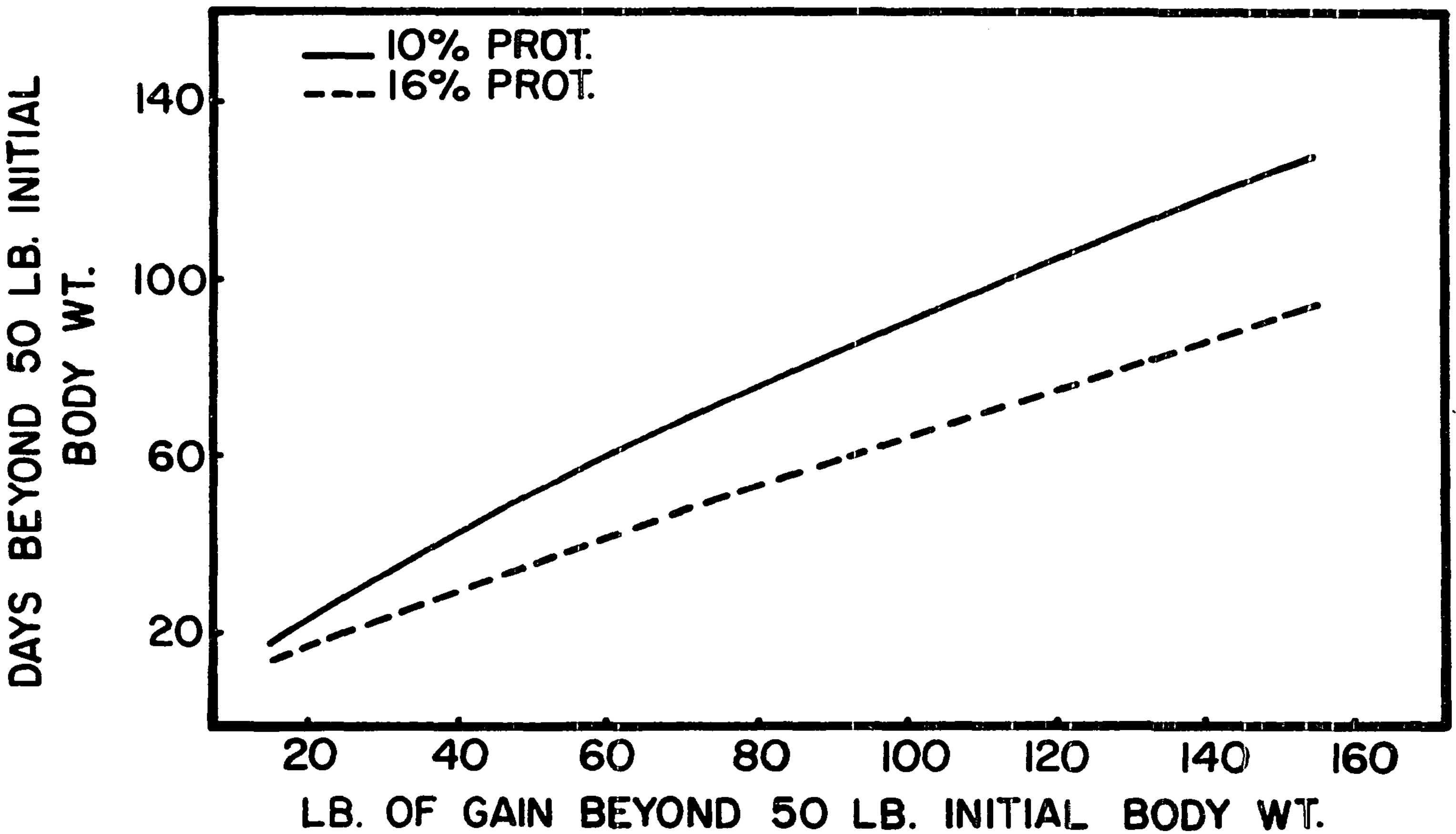
It was previously noted that the 10 percent protein level required the most time to produce the gain specified at each contour. When the number of days were rounded to the nearest day, it appeared that the 16 percent protein level produced a given amount of gain in the least time. Therefore, estimates of the days required to produce a given gain with the two protein levels were plotted for the purpose of comparison. Figures 24, 25 and 26 illustrate the estimates for the individual and combined sets of data. The differences in time between the most and least time paths tend to become wider as the amount of gain is increased. The rate at which time decreases per pound of gain diminishes rapidly between 20 and 60 pounds of gain but more slowly thereafter until it finally increases.

Figure 24. **Experiment** 6323 - comparison of time curves predicted by the square root function (equation 6.1) for protein levels corresponding to the most and least time paths



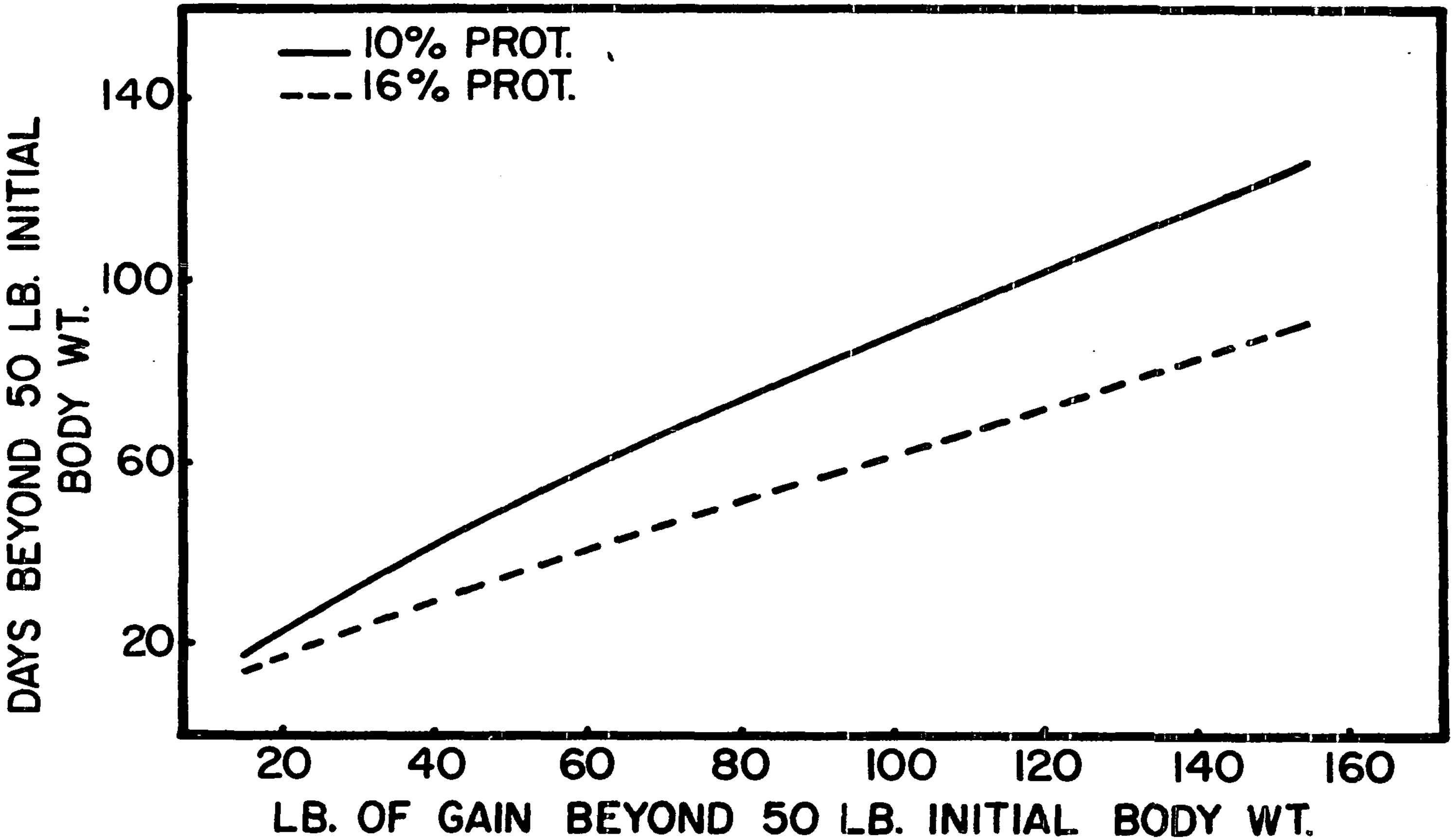
10% PROT.
16% PROT.
DAYS BEYOND 50 LB. INITIAL BODY WT.
140
100
60
20
20
40
60
80
100
120
140
160
LB. OF GAIN BEYOND 50 LB. INITIAL BODY WT.

Figure 25. **Experiment 6335** - comparison of time curves predicted by the square root function (equation 6.3) for protein levels corresponding to the most and least time paths



10% PROT.
16% PROT.
DAYS BEYOND 50 LB. INITIAL BODY WT.
140
100
60
20
20
40
60
80
100
120
140
160
LB. OF GAIN BEYOND 50 LB. INITIAL BODY WT.

Figure 26. Combined experiments 6323, 6335 - comparison of time curves predicted by the square root function (equation 6.5) for protein levels corresponding to the most and least time paths


10% PROT.
16% PROT.
DAYS BEYOND 50 LB. INITIAL BODY WT.
140
100
60
20
20
40
60
80
100
120
140
160
LB. OF GAIN BEYOND 50 LB. INITIAL BODY WT.

GENERAL DISCUSSION

Effect of Protein Level on Performance

Average daily gain

Protein levels of 20 percent (summer) and 18 percent (winter) produced maximum daily gains for growing pigs during the 50 to 110 pound interval. The highest average daily gain during the 110 to 205 pound period was noted at 14 percent protein in two trials. Maximum daily gains resulted at protein levels of 16 percent (summer) and 14 percent (winter) when constant protein levels of 10 to 20 percent were provided throughout the growing-finishing period. These results, in reference to maximum daily gain for the entire period, are consistent with those of Jensen *et al*. (1955), Jensen (1953), Lassiter *et al*. (1955), Reimer and Meade (1964), and Speer *et al*. (1956).

Adequate response was obtained at the lowest protein level (10 percent) where the daily gain averaged 1.21 pounds (summer) and 1.15 pounds (winter) over the entire period. These data are in agreement with the results of Jensen *et al*. (1955) who found a response of 1.30 pounds average daily gain (summer) over the entire period in a similar study. They obtained a response of 1.47 pounds average daily gain on 10 percent protein in the winter. However, the fact that the winter trial by Jensen *et al*. (1955) was conducted inside at a warm temperature might account for the difference. The studies of Jensen (1953), Jensen et al. (1955), Becker et al. (1955) and Speer et al. (1956), as well as the study reported herein, suggest that weight gain to 205 pounds can be attained in a reasonable length of time by pigs consuming a 10 percent protein ration either in drylot or on pasture.

The third trial of the study reported herein indicated that the response of the pig during the 46 to 110 pound interval (early) had little effect on the response shown during the 110 to 205 pound period (late). Pigs which had received 20 percent protein (early) produced slower gains while receiving 9 percent protein (late), suggesting a negligible effect from the high protein level in the early period. The response of the pigs on 20 percent protein (late) was more than double the response which they had shown on 10 percent protein (early), thus indicating no depressing effect from low protein in the early period. Pigs which had been on protein levels of 10 to 20 percent (early) and were then switched to 12 percent protein (late) produced strikingly similar gains.

One would not expect an effect from protein since there is little storage of this nutrient from day to day. However, energy is stored in the form of fat depots in the body. Thus, some effect might result from the carbohydrates in the diet.

Feed efficiency

The least amount of feed required per pound of gain was found at 20 percent protein during the 50 to 110 pound period in both trials. Protein levels of 14 percent (summer) and 12 percent (winter) resulted in maximum feed efficiency for the interval of 110 to 205 pounds. Maximum feed efficiency was attained at protein levels of 14 percent (summer) and 16 percent (winter) over the entire experimental period. The results concerning maximum feed efficiency for the total period are in agreement with those of Jensen (1953), Speer _et al_. (1956), Reimer and Meade (1964), and Lassiter _et al_. (1955).

Feed required per pound of gain was greater than that noted by Jensen _et al_. (1955), especially at the 10 percent protein level in the winter trial. Again, this aggravated effect might have been due to the fact that the study of Jensen _et al_. (1955) was conducted inside at a warm temperature. They obtained maximum feed efficiency at 12 percent protein over the entire production period in both trials.

The trend in feed efficiency parallelled the trend in average daily gain for experiments 6323 and 6335. The overall feed conversion for the summer trial was improved over that of the winter trial, as might be expected.

A slight effect from protein level in the early period on feed efficiency in the later period was noted in the trial conducted to compare changes in protein levels. A significant linear regression of feed required per pound of gain on protein level for the pigs on 12 percent protein (late) indicated some carry-over effect from the higher protein levels fed during the early period. However, the increasing protein levels (early) produced a decreasing effect on feed efficiency in the later period, contrary to what might be expected.

Pigs which had been on 10 percent protein (early) produced a marked improvement in feed efficiency on 20 percent protein (late), parallelling the trend in average daily gain. Pigs which were on 20 percent protein (early) and were switched to 9 percent protein (late) required considerably more feed per pound of gain than did those switched to 12 percent protein (late).

In summary, the results of Experiment 6417 indicate that the response of the pig in an initial weight period exerts a negligible effect on the response in a subsequent period. The only exception noted was the decrease in feed efficiency, by pigs on 12 percent protein (late), corresponding to the increase in protein level in the early period. However, this effect is contrary to what one might expect.

Effect of Protein Level on Carcass Quality

Percent ham and loin

Significant linear and quadratic or cubic regressions of ham and loin percent on protein level were noted in the trials providing protein levels of 10 to 20 percent throughout the entire experimental period. A protein level of 20 percent resulted in the maximum percent ham and loin of the carcass in both trials. These results are consistent with Ashton *et al.*

(1955) who obtained a maximum in percent lean cuts at a protein level of 20 percent in a similar summer trial. However, these workers noted maximum percent lean cuts at 16 percent protein in a winter trial conducted inside at a warm temperature.

The results of the study reported herein are also in accordance with other workers who noted a consistent increase in percent lean cuts as the protein level was increased (Becker *et al.*, 1962; Kropf *et al.*, 1959; Noland and Scott, 1960; Wagner *et al.*, 1963; Seerley *et al.*, 1964; Hays *et al.*, 1963; Robison *et al.*, 1952; Wilson *et al.*, 1953).

The response in ham and loin percent to protein level in the late period was affected little by the ration fed in the early period in the third trial. Percent ham and loin was significantly higher for pigs on the 10 percent (early) and 20 percent (late) protein levels when compared to the 20 percent (early) and 9 percent (late) protein levels. Pigs which were on 10 to 20 percent protein levels (early) and switched to 12 percent protein (late) exhibited little difference in percent ham and loin.

Carcass yield

Significant quadratic regressions of dressing percent on protein level were noted in the constant protein level trials. Maximum dressing percent existed at 12 percent protein in Experiment 6323 and at the 12 and 14 percent protein levels in Experiment 6335. This is in agreement with the work of Becker _et al_. (1962), Kropf _et al_. (1959), Wagner _et al_. (1963), Seerley _et al_. (1964) and Wallace _et al_. (1963).

Carcass yield appeared to be inversely related to percent ham and loin in both trials. Ham and loin percent increased as dressing percent decreased and vice versa.

Dressing percent was not significantly affected by the change in protein level in the third trial.

Carcass backfat

A significant linear regression of carcass backfat on protein level existed in each of the constant protein level trials. Protein levels of 20 percent (summer) and 18 percent (winter) resulted in the minimum amount of backfat. Pigs on the 10 percent protein level contained the most amount of backfat. The carcass backfat measurements for all experimental treatments were lower for the winter trial than for the summer trial, as might be expected.

Carcass backfat was slightly affected by protein level change in the third trial. Pigs which were on 10 to 20 percent protein levels (early) and switched to 12 percent protein (late) exhibited a linear decrease in backfat corresponding to the increase in protein level.

Carcass grade

The least number of pigs grading U.S. No. 1 was noted at a protein level of 10 percent on both trials. Grade was generally improved as the protein level in the ration was increased. However, the percentage of pigs grading U.S. No. 1 attained a maximum at 16 percent protein in the winter trial.

Protein levels of 10 percent (early) and 12 percent (late) resulted in the least number of pigs grading U.S. No. 1 in the third trial. The change in protein level did not otherwise affect carcass grade.

The Production Function

Choice of function

The quadratic and square root functions which were examined as alternatives for representing gain as a function of corn and soybean meal consumption exhibit similar properties. Both functions express changing elasticities of production for corn and soybean meal and will allow, but not force, either resource to be expressed as limiting factors of production. The quadratic forms also allow the mixture of corn and soybean meal to be changed as the gain of the pig proceeds over the production surface. The square root function declines less rapidly than the quadratic as the levels of inputs of corn and soybean meal are increased.

However, the substitution rates derived from the quadratic were increasing for the 10, 11, 12 and 13 percent protein rations as the pig increased in weight. These results agree with those of Woodworth (1954) who found similar behavior in the substitution rates of a quadratic function in an equivalent study. This suggests that pigs at heavier weights placed a higher relative value on soybean meal than on corn. It is not consistent with nutritional logic.

Furthermore, the square root function accounted for slightly more of the variation in gains than did the quadratic. This may have indicated that gain actually declined less rapidly at large feed inputs than would have been expected with the quadratic function.

For these reasons the square root function was chosen to represent the relation between gains and feed consumption in all sets of data.

It was expected that the function might not fit the extreme protein levels as close as the intermediate protein levels. However, plots of the fit of the function to the 10 and 20 percent protein levels revealed that the function provided extremely close estimates of the experimental observations.

Gain contours

Gain contours were selected to approximate the gain which might be expected over intervals of two weeks. It was believed that most producers do not store complete ground and mixed rations for periods in excess of two weeks and would be willing to change the ration every two weeks to reduce costs.

The contours for the two trials were proximate, although the contours in the winter trial were situated at larger corn and soybean meal inputs than those in the summer trial. This indicated that smaller inputs of corn and soybean meal were required to produce an equal amount of gain in the summer trial. This is consistent with what one might expect since energy requirements for maintenance are higher in the winter.

Marginal productivity of feed

A shift in the proportions of corn and soybean meal resulting in the highest marginal productivities for the increasing feed inputs over gain intervals was observed in both trials. The shift followed a path over lower protein levels as feed inputs and gain outputs were increased. One might also expect this because the pig requires a lesser amount of protein and a greater amount of carbohydrates as the production period is extended.

Although exceptions were noted, the data showed that marginal feed productivity declined with increasing inputs of feed and outputs of gain. The results of the data, concerning marginal productivity for increasing feed input, are consistent with those obtained by Woodworth (1954) and McKee (1955).

Marginal Rates of Substitution

The substitution rates displayed similar properties for all sets of data. Substitution rates at the gain contours decreased as the level of protein was increased in the ration. Also, the substitution rates decreased at a given protein level as the amount of gain was increased. These data compare closely with the data of Woodworth (1954), who also examined a square root function.

An exception was noted in the study reported herein at the 75 pound gain contour where the substitution rates increased for the 10 percent protein level. This was probably due to the replacement of minerals and vitamins with corn as explained previously. Thus, it did not present a major problem.

Equivalent properties were observed for the substitution rates determined for the gain intervals. The substitution rates between gain contours should be more applicable to production conditions since they are more accurate and may be utilized for a range in the weight of the pig.

The properties of the substitution rates determined in these trials are similar to those of substitution rates determined from other functions examined by McKee (1955) and Woodworth (1954).

Cost Minimization of Feed

Feed costs are minimized by selection of a ration designated by the substitution rate which is equal to the price ratio of the inputs. For example, the price ratio of soybean meal to corn is 2.5 when the prices of corn and soybean meal are 2¢ and 5¢ per pound, respectively. It is obvious that feed costs may be reduced if the ration presently being fed exhibits a substitution rate of 2.0, since two pounds of corn costing 4¢ will replace one pound of soybean meal costing 5¢.

It may not be obvious if the producer must conduct many calculations in order to determine the combination of ingredients which results in the minimum cost of the ration.

The following method of presentation of the least cost ration technique appears to be desirable and relatively uncomplicated. The method requires the following tables: (1) a table showing a series of price ratios corresponding to the price of corn per bushel on one axis and the price of soybean meal per pound on the other axis, (2) a table containing substitution rates of soybean meal for corn for the eleven protein levels (10 to 20 percent) over the seven gain intervals (0 to 155 pounds of gain) and (3) a table containing the compositions of the 22 rations corresponding to the protein levels of 10 to 20 percent. Two sets of rations would be required to account for the reduction of minerals and vitamins at 110 pounds of body weight. The price of corn would have been converted to a per pound basis for calculation of the price ratios. However, ease in the use of the table would be facilitated by listing the price of corn on a per bushel basis. The intervals of gain correspond to those which were used in this study.

The procedure of minimization of feed costs is now relatively simple. The producer would enter the table of price ratios at those points corresponding to the prices of corn and soybean meal and locate the price ratio. He would then find the corresponding substitution rate and protein level for the proper weight interval in the table of substitution rates. Finally, he would mix the ration in the proportions designated in the third table by the protein level from the second table.

The changes in ham and loin percent between adjacent protein levels at market weight (155 pounds of gain), as well as days required over each gain interval, could be listed in a fourth table. Thus, the producer would be able to compare these effects on pork production costs with the savings in feed costs.

Producers are gaining more education and are becoming more aware of cost reduction methods. In addition, rations are probably not stored for periods longer than two weeks, if for that long. Therefore, it seems reasonable that they would be interested in this uncomplicated method of minimizing feed costs at each two week interval. Of course, the necessity for changing the ration as often as every two weeks depends on the magnitude of the cost saving which might be accomplished. If the cost saving is negligible, longer time intervals would be acceptable.

Ham and Loin Functions

Predicted ham and loin percent

Several functions were examined as alternatives for expressing the relationship between ham and loin percent and corn and soybean meal combinations. While some variation existed among the functions concerning prediction of ham and loin percent, the data generally showed that the predicted values were comparatively close to the observed values. The predicted values at low levels of protein were closer to the observed values than those at high protein levels in Experiment 6323. In Experiment 6335, the predicted values slightly underestimated the observed values at low protein levels. All of the functions predicted values which compared quite closely with the average of the observed values which were combined for the two trials.

None of the functions accurately estimated the observed ham and loin percent at the 18 percent protein level in either the individual or combined sets of data. However, the effect of a marked decrease in ham and loin percent at that protein level is not readily explainable. One would expect a ham and loin percent which would be intermediate to those at 16 and 20 percent protein, whether increasing or decreasing over that range in protein levels. Nevertheless, the functions in all of the data produced an increasing trend in ham and loin percent which might be expected over the range in protein levels (10 to 20 percent).

Examination of the change in ham and loin percent (between adjacent protein levels) revealed a great deal of variation between the observed change and that predicted by each function. Much of this variation may have been due to the decrease in observed ham and loin percent at the 18 percent protein level. The functions appeared to provide estimates of the observed change in ham and loin percent which were more accurate for the combined data than for either of the individual trials. The change in ham and loin percent followed a trend which might reasonably be expected. That is, the increase in ham and loin percent occurred at a diminishing rate with the exception of the decrease noted between 18 and 20 percent protein in Experiment 6323.

Choice of function

The square root function (without interaction) predicted values which were closer estimates of observed ham and loin percent than the remaining functions at most of the protein levels. In addition, the square root function accounted for a greater proportion of the variation in ham and loin percent than any other function in Experiment 6323 and for the combined data. This function fitted the data in Experiment 6335 almost as closely as did the quadratic ratio, which accounted for the largest amount of variation in ham and loin percent in that trial. Therefore, the square root function appeared to be the appropriate choice.

Prediction of Time

Both of the quadratic and square root functions predicted similar estimates of the time required to produce a given gain for a specified protein level. The square root function explained a larger proportion of the variation in time and, thus, appeared to be the appropriate choice.

Estimates of time

The marginal or added time required to produce an added pound of gain decreased over the five intervals for the first 100 pounds of gain. This effect was noted for each protein level in the individual and combined sets of data. Marginal time was increased over the subsequent gain interval (100 to 125 pounds) for protein levels higher than 13 to 16 percent for all of the data. Marginal time increased over the last interval for all protein levels except 10 and 11 percent in Experiment 6335 and 10 percent in the combined data. This indicated a plateauing of the rate of gain over the last interval, probably due to the effect described in Experiment 6323.

The extreme protein levels resulted in more days required to produce a given gain over each gain interval. The least time path was noted at successively lower protein levels as the gain intervals corresponding to heavier weights were attained. The protein level consistent with the least time path decreased from approximately 18 to 15 percent protein as the weight of the pig was increased. Woodworth (1954) obtained similar results in an equivalent study.

Similar predictions of the number of days required by the pig to attain each gain contour for each protein level were obtained in all of the sets of data. A larger number of days was required to produce pigs of market weight on the extreme than on the intermediate protein levels. This effect was noted by Woodworth (1954) at gain contours of 109 and 191 pounds. Approximately 35 more days were required to produce 155 pounds of gain on 10 percent protein as compared to the least time ration of 16 percent protein. The least time path followed a higher level of protein over the production period at the gain contours than over the gain intervals. These results are in agreement with those of Woodworth (1954).

SUMMARY

Three growing-finishing swine experiments involving 360 pigs were conducted; first, to determine the substitution rate of soybean meal for corn from production functions fitted to the data derived from feeding constant protein levels (based on a reduction of minerals and vitamins commensurate with increasing weight of the pig); second, to determine the effect of a change in the components of the ration on carcass quality; third, to test the assumption, underlying the least cost ration technique, that the response of the pig in a given weight period exerts a negligible effect on the response in subsequent weight periods.

There were significant linear and quadratic regressions of average daily gain on protein level for the 50 to 110 pound period in the two trials conducted to evaluate constant protein levels. Significant linear, quadratic and cubic regressions of average daily gain on protein level existed for the 110 to 205 pound interval and for the entire experimental period. Maximum gains for the entire period occurred at the 16 percent (summer) and 14 percent (winter) protein levels.

Significant linear, quadratic and cubic regressions of feed required per pound of gain on protein level were determined for each stage of the production period as well as for the entire period in both trials. Maximum feed efficiency was noted at protein levels of 14 percent (summer) and 16 percent

(winter) for the entire period. Adequate performance was obtained at the lowest protein level (10 percent) in both trials.

Significant linear and quadratic, and significant linear and cubic regressions of ham and loin percent on protein level were obtained. A protein level of 20 percent resulted in the maximum percent ham and loin of the carcass in both trials. There were significant quadratic regressions of dressing percent on protein level with the maximum existing at the 12 percent (summer) and 12 to 14 percent (winter) protein levels. Dressing percent appeared to be inversely related to ham and loin percent in both trials. A significant linear regression of carcass backfat on protein level was noted in each trial. Minimum backfat occurred at protein levels of 20 percent (summer) and 18 percent (winter).

Results of the third trial essentially indicated that the response of the pig to protein level in the initial weight interval (46 to 110 pounds) exerted little effect on the response in the final weight period (110 to 205 pounds). An exception was the significant linear decrease in feed efficiency during the later period resulting from a linear increase in protein level in the early period. Neither ham and loin percent nor dressing percent were affected by the change in protein level. Pigs which were on 10 to 20 percent protein levels (early) and were switched to 12 percent protein (late) exhibited a significant linear decrease in carcass backfat corresponding to the increase in protein level.

The data for the effect of constant protein level on average daily gain, feed required per pound of gain, percent ham and loin, and days required over the production period were combined for the two constant protein level trials. There were no significant season times protein level interactions for any of the criteria tested. Therefore, the economic interpretation of the data was based on the combined trials, as well as on each individual trial. Significant linear, quadratic and cubic regressions of all of the criteria on protein level were determined for the combined data.

Quadratic and square root equations were examined as alternative production functions for expressing the relationship between body weight gain and the consumption of corn and soybean meal. Each of the functions were fitted to the observations from the six protein levels (10 to 20 percent) in the individual and combined sets of data. The square root function accounted for more of the variation in gain than did the quadratic. The substitution rates derived from the quadratic were inconsistent. Thus, the square root function was utilized for the prediction of marginal feed productivities and substitution rates.

Gain contours of 15, 35, 55, 75, 100, 125 and 155 pounds (beyond 50 pounds body weight) were selected to approximate the gain which might be expected over intervals of two weeks. The gain contours for the summer trial were similar to those of the winter trial, although they existed at lower levels of corn and soybean meal inputs.

The total amounts of gain beyond 50 pounds initial weight were determined for incremental feed inputs of 50 pounds. Marginal feed productivities were calculated for the increments of feed and for the gain intervals between gain contours. Although exceptions were noted, the data showed that the marginal productivity of feed declined with increasing inputs of feed and increasing outputs of gain. The proportions of corn and soybean meal which maximized marginal feed productivity shifted to lower protein levels as feed inputs and gain outputs were increased. A similar shift was noted in the trend of total gains.

The marginal rates of substitution of soybean meal for corn were determined at the gain contours for eleven protein levels (10 to 20 percent). The substitution rates declined at a given protein level as the pig increased in weight. Similarly, they decreased at a given gain contour as the level of protein was increased in the ration. In addition, substitution rates were determined as averages between each gain contour in order that they might be more accurate and applicable to a range in weight of the pig over each gain interval. The properties of the substitution rates over the gain intervals were equivalent to those noted for the substitution rates determined at the gain contours.

The condition for minimization of feed costs is that the marginal rate of substitution of soybean meal for corn in the ration must be equated to the soybean meal/corn price ratio. Selection of the combination of corn and soybean meal designated by the substitution rate will result in a ration for which cost is a minimum. The process of minimization of feed costs was demonstrated over gain intervals for various weights of pigs. A method designed for the application of the least cost ration technique by the producer was also presented.

Several functions were examined as alternatives for expressing the relationship between percent ham and loin of the carcass and combinations of corn and soybean meal. The corn and soybean meal combinations (reflecting protein level) were total inputs corresponding to the ham and loin percent determined at market weight.

Values of percent ham and loin at market weight (155 pounds of gain) were predicted from the functions for the eleven protein levels. The predicted ham and loin percents constituted reasonably accurate estimates of the observed values with the exception of the observation at the 18 percent protein level.

The change in ham and loin percent between adjacent protein levels was calculated from the predicted values. Examination of the change in ham and loin percent revealed much variation between the observed change and that predicted by each function, partially due to the observation at the 18 percent protein level. However, the change in ham and loin percent followed an expected trend in that the increase occurred at a diminishing rate as the protein level was increased.

Of the alternatives examined, the square root function predicted more accurate estimates of the observations of ham and loin percent. Since the square root function also explained a larger proportion of the variation in ham and loin percent, it appeared to be the appropriate choice.

Quadratic and square root functions were also examined as alternatives for expressing marginal time per pound of gain as a function of the percent protein in the ration and the marginal gain over intervals of two weeks. Both functions predicted similar estimates of the time required to produce a pound of gain. The square root function was chosen for prediction of marginal days per pound of gain because it accounted for more of the variation in time.

The marginal time required to produce a marginal pound of gain decreased over the five intervals for the first 100 pounds of gain. However, marginal time increased at protein levels of 13 to 16 percent for the interval of 100 to 125 pounds and for all protein levels except 10 percent for the last interval. Thus, the rate of gain plateaued over the last interval.

The number of days required to produce a given amount of gain over each gain interval was calculated from the predictions of marginal days per pound of gain. The extreme protein levels required more days to produce a given gain over each gain interval. The protein level consistent with the least time path decreased from approximately 18 to 15 percent protein as the weight of the pig was increased.

The number of days required to attain each gain contour was calculated by addition of the quantities over each gain interval. Approximately 35 more days were required to produce 155 pounds of gain on 10 percent protein as compared to the least time ration of 16 percent protein. A 20 percent protein ration required approximately six more days to produce 155 pounds of gain than did the 16 percent protein level.

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APPENDIX

Table 1. Minimum nutrient requirements used as a basis for calculation of all experimental rations[a]

Item	Unit	Body weight (lb.) 40-75	75-150	150-200
Protein	%	15	13	12
Calcium	%	0.65	0.50	0.50
Phosphorus	%	0.50	0.40	0.40
Vitamin A	I.U./lb.	400	400	400
Vitamin D_2	I.U./lb.	90	60	60
Riboflavin	mg./lb.	1.2	1.0	1.0
Pantothenic acid	mg./lb.	5.0	4.5	4.5
Niacin	mg./lb.	6.0	5.0	5.0
Vitamin B_{12}	mcg./lb.	5.0	5.0	5.0
Antibiotic	mg./lb.	5-10	5	5

[a]Values taken from National Research Council, Publication 648, Nutrient Requirements of Swine, 1959.

Table 2. Composition of mineral and vitamin premixes

Mineral premix		Vitamin premix	
Calcium carbonate	11.0	Chlortetracycline, gm.	20.00
Dicalcium phosphate	22.0	Vitamin A, I.U.	1,000,000
Iodized salt	10.0	Vitamin D_2, I.U.	299,600
Trace mineral mix (35-C-41)	1.0	Riboflavin, gm.	2.00
Ground yellow corn	6.0	Pantothenic acid, gm.	4.00
		Niacin, gm.	9.00
Total (lb.)	50.0	Vitamin B_{12}, mg.	10.00
		Ground yellow corn, lb.[a]	46.89
		Total (lb.)	50.00

[a]48.64 in Experiment 6417.

Table 3. Composition of trace mineral mix (35-C-41)

Element	Percent in premix	Parts per million added to ration[a]
Iron	7.000	35.00
Copper	0.475	2.38
Cobalt	0.166	0.83
Manganese	5.680	28.40
Zinc	8.100	40.50
Potassium	0.750	3.75
Calcium	5.280	-----

[a]When added at 0.05 percent of ration.

Table 4. Experiments 6323, 6335 - composition of experimental rations[a]

Ingredient	Percent protein					
	10	12	14	16	18	20
Ground yellow corn	91.20	86.50	81.75	77.05	72.35	67.60
Solvent soybean meal (50% protein)	3.80	8.50	13.25	17.95	22.65	27.40
Mineral premix	2.50	2.50	2.50	2.50	2.50	2.50
Vitamin premix	2.50	2.50	2.50	2.50	2.50	2.50
Total (lb.)	100.00	100.00	100.00	100.00	100.00	100.00

[a]Body weight of 40 to 110 lb.

Table 5. Experiments 6323, 6335 - calculated analysis of experimental rations[a]

Item	Unit	Percent protein 10	12	14	16	18	20
Protein	%	10.00	12.00	14.01	16.00	17.99	20.01
Calcium	%	0.52	0.52	0.53	0.54	0.55	0.56
Phosphorus	%	0.46	0.48	0.50	0.51	0.53	0.55
Vitamin A	I.U./lb.	1438	1391	1344	1297	1250	1202
Vitamin D_2	I.U./lb.	150	150	150	150	150	150
Riboflavin	mg./lb.	1.52	1.54	1.58	1.62	1.65	1.68
Pantothenic acid	mg./lb.	4.30	4.47	4.65	4.84	5.01	5.19
Niacin	mg./lb.	13.97	13.96	13.95	13.94	13.93	13.92
Choline	mg./lb.	237	280	341	393	445	497
Vitamin B_{12}	mcg./lb.	5.00	5.00	5.00	5.00	5.00	5.00
Chlortetracycline	mg./lb.	10.00	10.00	10.00	10.00	10.00	10.00

[a]Body weight of 40 to 110 lb.

Table 6. Experiments 6323, 6335 - composition of experimental rations[a]

Ingredient	Percent protein					
	10	12	14	16	18	20
Ground yellow corn	93.95	89.25	84.50	79.80	75.05	70.35
Solvent soybean meal (50% protein)	3.55	8.25	13.00	17.70	22.45	27.15
Mineral premix	1.25	1.25	1.25	1.25	1.25	1.25
Vitamin premix	1.25	1.25	1.25	1.25	1.25	1.25
Total (lb.)	100.00	100.00	100.00	100.00	100.00	100.00

[a]Body weight of 110 to 200 lb.

Table 7. Experiments 6323, 6335 - calculated analysis of experimental rations[a]

Item	Unit	Percent protein					
		10	12	14	16	18	20
Protein	%	10.00	12.00	14.01	16.00	18.01	20.01
Calcium	%	0.26	0.27	0.28	0.29	0.30	0.31
Phosphorus	%	0.36	0.38	0.40	0.42	0.44	0.46
Vitamin A	I.U./lb.	1203	1156	1108	1061	1014	967
Vitamin D_2	I.U./lb.	75	75	75	75	75	75
Riboflavin	mg./lb.	1.02	1.06	1.09	1.12	1.16	1.19
Pantothenic acid	mg./lb.	3.31	3.49	3.67	3.85	4.03	4.21
Niacin	mg./lb.	11.82	11.81	11.81	11.79	11.78	11.77
Choline	mg./lb.	237	288	341	392	444	496
Vitamin B_{12}	mcg./lb.	2.50	2.50	2.50	2.50	2.50	2.50
Chlortetracycline	mg./lb.	5.00	5.00	5.00	5.00	5.00	5.00

[a]Body weight of 110 to 200 lb.

Table 8. Experiment 6417 - composition of experimental rations

Ingredient	Percent protein[a]				Percent protein[b]		
	10	13.3	16.6	20	9	12	20
Ground yellow corn	91.20	83.40	75.60	67.60	96.30	89.25	70.35
Solvent soybean meal (50% protein)	3.80	11.60	19.40	27.40	1.20	8.25	27.15
Mineral premix	2.50	2.50	2.50	2.50	1.25	1.25	1.25
Vitamin premix	2.50	2.50	2.50	2.50	1.25	1.25	1.25
Total (lb.)	100.00	100.00	100.00	100.00	100.00	100.00	100.00

[a]Body weight of 40 to 110 lb.

[b]Body weight of 110 to 200 lb.

Table 9. Experiment 6417 - calculated analysis of experimental rations

Item	Unit	Percent protein[a]				Percent protein[b]		
		10	13.3	16.6	20	9	12	20
Protein	%	10.00	13.31	16.61	20.01	9.00	12.00	20.01
Calcium	%	0.52	0.53	0.54	0.56	0.26	0.27	0.31
Phosphorus	%	0.46	0.49	0.52	0.55	0.35	0.38	0.46
Vitamin A	I.U./lb.	1439	1361	1283	1203	1226	1156	967
Vitamin D_2	I.U./lb.	150	150	150	150	75	75	75
Riboflavin	mg./lb.	1.52	1.57	1.62	1.68	1.00	1.06	1.19
Pantothenic acid	mg./lb.	4.30	4.59	4.88	5.19	3.22	3.49	4.21
Niacin	mg./lb.	13.97	13.95	13.93	13.92	11.82	11.81	11.77
Choline	mg./lb.	242	328	414	502	213	291	499
Vitamin B_{12}	mcg./lb.	5.00	5.00	5.00	5.00	2.50	2.50	2.50
Chlortetracycline	mg./lb.	10.00	10.00	10.00	10.00	5.00	5.00	5.00

[a]Body weight of 40 to 110 lb.

[b]Body weight of 110 to 200 lb.

Table 10. Experiment 6323 - summary of the effect of protein level on average daily gain (lb.)

Rep.	Percent protein 10	12	14	16	18	20
50 lb. to 110 lb.						
1	1.05	1.16	1.56	1.64	1.77	1.76
2	1.11	1.28	1.41	1.43	1.57	1.59
3	1.05	1.42	1.54	1.65	1.49	1.58
4	1.19	1.50	1.61	1.74	1.57	1.59
5	1.14	1.37	1.68	1.62	1.61	1.64
Avg.	1.11	1.35	1.56	1.62	1.60	1.63
110 lb. to 205 lb.						
1	1.21	1.75	2.01	1.79	1.90	1.65
2	1.31	1.77	1.98	1.73	1.83	1.78
3	1.08	1.94	1.93	1.88	1.76	1.77
4	1.43	1.68	1.69	1.78	1.85	1.77
5	1.42	1.73	1.75	1.90	1.73	1.76
Avg.	1.29	1.77	1.87	1.82	1.81	1.75
Total experiment						
1	1.14	1.47	1.75	1.73	1.85	1.70
2	1.22	1.53	1.72	1.60	1.71	1.69
3	1.07	1.67	1.75	1.77	1.64	1.69
4	1.33	1.60	1.66	1.76	1.72	1.69
5	1.29	1.56	1.72	1.77	1.68	1.71
Avg.	1.21	1.57	1.72	1.73	1.72	1.70

Table 11. Experiment 6323 - summary of the effect of protein level on feed required per pound of gain (lb.)

Rep.	Percent protein					
	10	12	14	16	18	20
50 lb. to 110 lb.						
1	4.30	3.51	2.90	2.70	2.67	2.68
2	3.78	3.22	3.02	3.14	2.95	2.96
3	3.68	3.24	2.98	2.88	3.03	2.90
4	3.70	3.11	2.77	2.79	3.03	2.78
5	3.77	3.12	2.87	2.90	2.79	2.77
Avg.	3.85	3.24	2.91	2.88	2.89	2.82
110 lb. to 205 lb.						
1	5.18	3.93	3.52	3.92	3.67	4.06
2	4.82	3.70	3.38	3.91	4.07	4.11
3	4.55	3.64	3.69	3.91	4.01	3.75
4	4.48	3.86	3.79	4.02	4.00	3.59
5	4.46	3.81	3.89	3.76	4.10	4.07
Avg.	4.70	3.79	3.65	3.90	3.97	3.92
Total experiment						
1	4.81	3.79	3.21	3.47	3.27	3.50
2	4.39	3.51	3.24	3.61	3.59	3.62
3	4.18	3.46	3.40	3.46	3.62	3.40
4	4.19	3.54	3.40	3.53	3.58	3.29
5	4.14	3.52	3.45	3.40	3.54	3.51
Avg.	4.34	3.56	3.34	3.49	3.52	3.46

Table 12. Experiment 6323 - summary of the effect of protein level on percent ham and loin, and carcass backfat

Rep.	Percent protein 10	12	14	16	18	20
Ham and loin[a]						
1	36.21	38.80	38.19	38.42	38.29	37.91
2	35.49	36.36	38.31	35.76	35.92	38.95
3	35.86	36.33	36.28	37.68	37.45	38.33
4	34.00	35.95	36.66	37.92	36.66	38.34
5	34.34	35.57	36.52	36.66	36.87	36.48
Avg.	35.18	36.60	37.19	37.29	37.04	38.00
Carcass backfat (in.)						
1	1.67	1.44	1.44	1.45	1.45	1.57
2	1.51	1.56	1.41	1.75	1.56	1.44
3	1.49	1.56	1.61	1.47	1.54	1.42
4	1.68	1.65	1.62	1.38	1.54	1.35
5	1.76	1.61	1.66	1.63	1.60	1.50
Avg.	1.62	1.56	1.55	1.54	1.54	1.46

[a]Weight as percent of chilled carcass weight.

Table 13. Experiment 6323 - summary of the effect of protein level on carcass yield, length and grade

Rep.	Percent protein 10	12	14	16	18	20
Carcass yield[a]						
1	69.12	69.74	69.71	69.14	68.94	68.89
2	68.79	69.06	69.08	69.62	69.15	69.25
3	69.80	70.63	69.18	69.46	70.80	68.41
4	69.52	69.82	69.27	68.96	68.28	67.86
5	67.91	69.10	69.86	68.48	69.54	68.27
Avg.	69.03	69.67	69.42	69.13	69.34	68.54
Carcass length (in.)						
1	30.1	29.8	30.5	30.3	31.0	29.9
2	29.5	29.8	29.8	29.4	29.8	29.7
3	29.6	30.5	30.0	29.9	29.6	30.0
4	29.4	29.8	29.3	29.6	30.0	30.2
5	29.3	30.0	29.6	29.9	29.3	29.8
Avg.	29.6	30.0	29.8	29.8	29.9	29.9

Carcass grade

Grade	No. pigs	%	No. pigs	%	No. pigs	%	No. pigs	%	No. pigs	%	No. pigs	%
1	6	32	12	67	13	65	14	70	13	65	17	85
2	11	58	6	33	6	30	6	30	7	35	3	15
3	2	10	0	0	1	5	0	0	0	0	0	0
Total	19	100	18	100	20	100	20	100	20	100	20	100

[a]Chilled carcass weight as percent of live weight.

Table 14. Experiment 6323 - analysis of variance plan and observed mean squares for average daily gain and feed required per pound of gain

Source of variation	d.f.	A.D.G.[a]	F/G[a]	A.D.G.[b]	F/G[b]
Replication	4	.0166	.0241	.0010	.0138
Protein level	5	.2192**	.7824**	.2296**	.6682**
linear	1	.8472**	2.7493**	.3925**	.6926**
quadratic	1	.2268**	.9648**	.5944**	1.5361**
cubic	1	.0101	.1898*	.1374**	1.0623**
remainder	2	.0059	.0042	.0119	.0250
Error	20	.0087	.0285	.0128	.0456
Total	29				

[a]Analysis for the 50 to 110 lb. period.

[b]Analysis for the 110 to 205 lb. period.

**Statistically significant at P = .01 or less, here and throughout the appendix.

*Statistically significant at P = .05 or less, here and throughout the appendix.

Table 15. Experiment 6323 - analysis of variance plan and observed mean squares for average daily gain, feed required per pound of gain, percent ham and loin, and carcass backfat, yield and length for the total experimental period

Source of variation	d.f.		A.D.G.	F/G	Ham and loin (%)	Carcass backfat	Carcass yield	Carcass length
Replication	4		.0022	.0106	2.9133*	.0141	.6676	.4078*
Protein level	5		.2069**	.6535**	4.5149**	.0143	.7637	.1037
linear		1	.5999**	1.3553**	17.1917**	.0605*	.9948	.1738
quadratic		1	.3840**	1.2672**	1.9001	.0001	1.7357*	.0669
cubic		1	.0490**	.6204**	3.1648*	.0006	.0271	.1179
remainder		2	.0008	.0123	.1588	.0100	.5304	.0800
Error	20		.0055	.0271	.6749	.0103	.3536	.1112
Total	29							

Table 16. Experiment 6335 - summary of the effect of protein level on average daily gain (lb.)

	Percent protein					
Rep.	10	12	14	16	18	20
51 lb. to 110 lb.						
1	0.85	1.24	1.28	1.38	1.65	1.55
2	0.96	1.31	1.45	1.40	1.38	1.41
3	1.05	1.21	1.48	1.51	1.57	1.48
4	1.05	1.43	1.37	1.35	1.44	1.37
5	1.09	1.38	1.67	1.30	1.38	1.37
Avg.	1.00	1.31	1.45	1.39	1.48	1.44
110 lb. to 205 lb.						
1	1.34	1.76	1.63	1.55	1.62	1.55
2	1.30	1.71	1.81	1.72	1.68	1.46
3	1.35	1.69	1.64	1.68	1.78	1.54
4	1.18	1.66	1.84	1.83	1.65	1.62
5	1.34	1.76	1.96	1.80	1.85	1.62
Avg.	1.30	1.72	1.78	1.72	1.72	1.56
Total experiment						
1	1.10	1.53	1.49	1.49	1.63	1.55
2	1.14	1.50	1.65	1.58	1.55	1.44
3	1.20	1.45	1.57	1.61	1.69	1.52
4	1.11	1.54	1.63	1.59	1.56	1.52
5	1.19	1.58	1.80	1.54	1.62	1.50
Avg.	1.15	1.52	1.63	1.56	1.61	1.51

Table 17. Experiment 6335 - summary of the effect of protein level on feed required per pound of gain (lb.)

Rep.	Percent protein 10	12	14	16	18	20
51 lb. to 110 lb.						
1	4.35	3.26	3.50	2.73	2.59	2.76
2	4.07	3.36	3.27	3.07	3.17	2.82
3	4.13	3.62	2.89	2.78	2.91	2.73
4	4.45	3.35	3.25	3.24	3.01	3.10
5	3.94	3.21	2.88	2.93	3.16	3.09
Avg.	4.19	3.36	3.16	2.95	2.97	2.90
110 lb. to 205 lb.						
1	4.77	3.84	4.46	4.32	4.46	4.27
2	4.72	3.92	4.46	4.61	4.13	4.13
3	4.62	4.20	3.91	3.83	3.92	4.18
4	5.63	4.01	4.22	3.96	4.12	4.12
5	4.89	3.88	3.88	3.70	4.30	4.45
Avg.	4.93	3.97	4.19	4.08	4.19	4.23
Total experiment						
1	4.61	3.64	4.13	3.80	3.74	3.74
2	4.46	3.66	3.99	4.02	3.77	3.65
3	4.41	3.96	3.52	3.43	3.50	3.61
4	5.05	3.70	3.85	3.64	3.68	3.74
5	4.38	3.60	3.38	3.37	3.83	3.84
Avg.	4.58	3.71	3.77	3.65	3.70	3.72

Table 18. Experiment 6335 - summary of the effect of protein level on percent ham and loin, and carcass backfat

	Percent protein					
Rep.	10	12	14	16	18	20
Ham and loin[a]						
1	37.29	37.59	38.54	39.47	39.28	39.59
2	36.38	38.39	38.50	37.94	39.08	39.26
3	35.70	37.00	37.90	38.26	39.07	38.62
4	35.33	37.21	39.20	38.40	38.95	39.16
5	36.65	37.68	36.64	40.47	37.73	39.45
Avg.	36.27	37.57	38.16	38.91	38.82	39.22
Carcass backfat (in.)						
1	1.46	1.40	1.28	1.23	1.16	1.28
2	1.36	1.37	1.27	1.52	1.25	1.30
3	1.50	1.40	1.35	1.18	1.24	1.34
4	1.59	1.44	1.21	1.34	1.21	1.22
5	1.47	1.26	1.50	1.24	1.47	1.29
Avg.	1.48	1.37	1.32	1.30	1.27	1.29

[a]Weight as percent of chilled carcass weight.

Table 19. Experiment 6335 - summary of the effect of protein level on carcass yield, length and grade

Rep.	Percent protein 10	12	14	16	18	20
Carcass yield[a]						
1	68.02	69.86	69.75	70.60	69.51	69.01
2	67.99	68.96	69.46	69.16	69.02	68.15
3	68.70	69.28	68.34	69.18	69.70	67.42
4	67.95	69.44	69.36	67.94	67.38	67.13
5	68.58	69.14	69.81	67.63	67.68	69.26
Avg.	68.25	69.34	69.34	68.90	68.66	68.19
Carcass length (in.)						
1	29.3	29.2	29.8	29.5	29.7	30.4
2	29.9	29.1	29.1	29.7	29.6	30.5
3	28.8	29.7	29.6	30.0	29.1	29.7
4	28.3	28.7	29.7	29.3	30.0	29.9
5	28.9	29.3	28.5	29.4	29.7	29.9
Avg.	29.0	29.2	29.3	29.6	29.6	30.1

Carcass grade

Grade	No. pigs	%	No. pigs	%	No. pigs	%	No. pigs	%	No. pigs	%	No. pigs	%
1	10	56	16	84	15	75	19	95	18	95	19	95
2	8	44	3	16	5	25	1	5	1	5	1	5
3	0	0	0	0	0	0	0	0	0	0	0	0
Total	18	100	19	100	20	100	20	100	19	100	20	100

[a]Chilled carcass weight as percent of live weight.

Table 20. Experiment 6335 - analysis of variance plan and observed mean squares for average daily gain and feed required per pound of gain

Source of variation	d.f.	A.D.G.[a]	F/G[a]	A.D.G.[b]	F/G[b]
Replication	4	.0046	.0520	.0180	.0730
Protein level	5	.1605**	1.1923**	.1563**	.5704**
linear	1	.4933**	4.3725**	.1063**	.6149*
quadratic	1	.2310**	1.3037**	.5720**	1.2290**
cubic	1	.0426	.2278*	.0642**	.5837*
remainder	2	.0177	.0288	.0194	.2122
Error	20	.0122	.0443	.0069	.0785
Total	29				

[a]Analysis for the 51 to 110 lb. period.

[b]Analysis for the 110 to 205 lb. period.

Table 21. Experiment 6335 - analysis of variance plan and observed mean squares for average daily gain, feed required per pound of gain, percent ham and loin, and carcass backfat, yield and length for the total experimental period

Source of variation	d.f.	A.D.G.	F/G	Ham and loin (%)	Carcass backfat	Carcass yield	Carcass length
Replication	4	.0049	.0734	.6090	.0038	1.2116	.1847
Protein level	5	.1565**	.6389**	6.0284**	.0298*	1.2834	.6811*
linear	1	.2840**	1.4310**	26.4028**	.1196**	.5386	3.2064**
quadratic	1	.4086**	1.1367**	3.1046*	.0270	4.5761**	.0720
cubic	1	.0563**	.3982**	.2477	.0004	1.0830	.0469
remainder	2	.0169*	.1142	.1933	.0010	.1097	.0402
Error	20	.0040	.0437	.5650	.0109	.5593	.1805
Total	29						

Table 22. Experiment 6417 - summary of the effect of protein level on average daily gain (lb.)

Rep.	Percent protein[a] 10 / 20	10 / 12	13.3 / 12	16.6 / 12	20 / 12	20 / 9
46 lb. to 110 lb.						
1	1.15	1.12	1.50	1.49	1.58	1.57
2	1.04	1.24	1.36	1.64	1.71	1.35
3	0.84	0.96	1.60	1.50	1.72	1.61
4	1.12	1.03	1.55	1.54	1.51	1.58
5	0.87	0.68	1.49	1.53	1.53	1.63
Avg.	1.00	1.01	1.50	1.54	1.61	1.55
110 lb. to 205 lb.						
1	1.80	1.71	1.72	1.65	1.73	1.44
2	2.06	1.79	1.78	1.83	1.75	1.27
3	2.21	1.80	1.76	1.84	1.79	1.42
4	1.88	1.56	1.77	1.84	1.62	1.38
5	2.31	1.83	1.84	1.76	1.78	1.56
Avg.	2.05	1.74	1.77	1.78	1.74	1.41
Total experiment						
1	1.48	1.43	1.64	1.59	1.68	1.48
2	1.46	1.53	1.60	1.74	1.73	1.30
3	1.39	1.36	1.68	1.69	1.76	1.50
4	1.47	1.29	1.66	1.71	1.62	1.45
5	1.37	1.03	1.67	1.65	1.66	1.59
Avg.	1.43	1.33	1.65	1.68	1.69	1.46

[a]Protein levels were adjusted at 110 lb. body weight as illustrated.

Table 23. Experiment 6417 - summary of the effect of protein level on feed required per pound of gain (lb.)

	Percent protein[a]					
Rep.	10 20	10 12	13.3 12	16.6 12	20 12	20 9
46 lb. to 110 lb.						
1	4.19	4.20	2.95	2.94	2.89	2.96
2	3.72	3.96	3.18	2.86	2.66	2.96
3	4.13	4.02	2.98	2.97	2.67	2.67
4	4.02	3.72	2.94	2.75	2.56	2.43
5	3.97	4.05	2.90	2.57	2.51	2.79
Avg.	4.01	4.01	2.99	2.82	2.66	2.76
110 lb. to 205 lb.						
1	3.45	3.74	3.61	3.85	3.94	4.73
2	3.19	3.63	3.61	3.88	3.75	4.61
3	3.15	3.47	3.65	3.84	3.92	4.33
4	3.27	3.53	3.73	3.56	3.56	4.66
5	2.79	3.24	3.66	3.64	3.59	4.30
Avg.	3.17	3.52	3.65	3.75	3.75	4.53
Total experiment						
1	3.73	3.94	3.38	3.54	3.57	4.10
2	3.41	3.76	3.45	3.42	3.32	4.02
3	3.51	3.68	3.37	3.50	3.36	3.63
4	3.58	3.61	3.37	3.25	3.17	3.77
5	3.28	3.61	3.34	3.18	3.13	3.61
Avg.	3.50	3.72	3.38	3.38	3.31	3.83

[a]Protein levels were adjusted at 110 lb. body weight as illustrated.

Table 24. Experiment 6417 - summary of the effect of protein level on percent ham and loin, and carcass backfat

	Percent protein[a]					
Rep.	10 20	10 12	13.3 12	16.6 12	20 12	20 9
Ham and loin[b]						
1	38.21	36.48	37.28	37.08	36.31	35.07
2	37.46	36.48	36.44	36.94	37.42	35.93
3	37.48	36.16	36.89	36.78	37.30	37.84
4	37.64	36.94	37.36	37.11	37.01	36.97
5	37.78	36.75	37.12	37.40	38.24	36.51
Avg.	37.71	36.56	37.02	37.06	37.26	36.46
Carcass backfat (in.)						
1	1.36	1.54	1.48	1.37	1.42	1.56
2	1.42	1.50	1.40	1.50	1.50	1.62
3	1.45	1.53	1.54	1.50	1.40	1.42
4	1.50	1.46	1.40	1.46	1.34	1.34
5	1.47	1.57	1.62	1.40	1.50	1.54
Avg.	1.44	1.52	1.49	1.45	1.43	1.50

[a]Protein levels were adjusted at 110 lb. body weight as illustrated.

[b]Weight as percent of chilled carcass weight.

Table 25. Experiment 6417 - summary of the effect of protein level on carcass yield, length and grade

Rep.	Percent protein[a] 10 / 20	10 / 12	13.3 / 12	16.6 / 12	20 / 12	20 / 9
Carcass yield[b]						
1	69.77	70.60	69.56	69.60	68.06	70.68
2	71.24	69.42	70.60	69.60	69.13	69.23
3	68.09	70.08	69.98	70.06	70.34	69.42
4	69.81	68.90	69.95	68.94	69.06	68.12
5	68.61	68.92	71.39	69.70	70.22	70.00
Avg.	69.50	69.58	70.30	69.58	69.36	69.49
Carcass length (in.)						
1	30.1	29.8	30.2	30.2	29.6	30.1
2	30.1	29.8	30.0	29.4	30.1	30.0
3	30.1	30.2	29.6	30.1	30.3	30.1
4	30.3	30.0	30.0	30.1	29.7	30.5
5	29.8	29.6	29.7	30.5	29.4	30.2
Avg.	30.1	29.9	29.9	30.1	29.8	30.2

Carcass grade

Grade	No. pigs	%	No. pigs	%	No. pigs	%	No. pigs	%	No. pigs	%	No. pigs	%
1	17	85	10	56	15	75	17	85	17	85	14	70
2	3	15	8	44	5	25	3	15	3	15	6	30
Total	20	100	18	100	20	100	20	100	20	100	20	100

[a]Protein levels were adjusted at 110 lb. body weight as illustrated.

[b]Chilled carcass weight as percent of live weight.

Table 26. Experiment 6417 - analysis of variance plan and observed mean squares for average daily gain and feed required per pound of gain[a]

Source of variation	d.f.	A.D.G.	F/G
Replication	4	.0126	.0786*
Protein level	5	.4015**	1.9778**
Trend	3	.3645**	1.7737**
linear	1	.7815**	4.1331**
quadratic	1	.2599**	1.0351**
cubic	1	.0520	.1529*
Common	2	.4571**	2.2840**
Error	20	.0172	.0211
Total	29		

[a]Analysis for the 46 to 110 lb. period.

Table 27. Experiment 6417 - analysis of variance plan and observed mean squares for average daily gain and feed required per pound of gain[a]

Source of variation	d.f.	A.D.G.	F/G
Replication	4	.0348	.0966**
Protein level	5	.2062**	.9976**
Low and high vs. carry-over	1	.0042	.2112**
Low vs. high	1	1.0176**	4.5968**
Carry-over	3		
Linear	1	.0000	.1568**
Quadratic	1	.0088	.0218
Cubic	1	.0003	.0014
Error	20	.0095	.0182
Total	29		

[a]Analysis for the 110 to 205 lb. period.

Table 28. Experiment 6417 - analysis of variance plan and observed mean squares for average daily gain, feed required per pound of gain, percent ham and loin, and carcass backfat, yield and length for the total experimental period

Source of variation	d.f.	A.D.G	F/G	Ham and loin (%)	Carcass backfat	Carcass yield	Carcass length
Replication	4	.0047	.1021**	.3628	.0085	.5194	.0620
Protein level	5	.1151**	.2173**	1.0577*	.0064	.5553	.0981
Extremes vs. carry-over	1	.1251**	.3125**	.0874	.0001	.2898	.3082
Among extremes	1	.0022	.2624**	3.9062**	.0078	.0005	.0250
Carry-over	3						
Linear	1	.3091**	.3807**	1.1300	.0234*	.4775	.0001
Quadratic	1	.1186**	.0911**	.0858	.0004	1.0811	.0845
Cubic	1	.0202	.0396	.0790	.0004	.9274	.0729
Error	20	.0104	.0106	.3184	.0052	.7988	.0838
Total	29						

Table 29. Combined experiments 6323, 6335 - summary of average daily gain, feed required per pound of gain, percent ham and loin, and days required for the total experimental period

	Percent protein					
	10	12	14	16	18	20
Average daily gain (lb.)						
	1.18	1.54	1.67	1.64	1.66	1.60
Feed/gain (lb.)						
	4.46	3.64	3.56	3.57	3.61	3.59
Ham and loin (%)						
	35.72	37.09	37.67	38.10	37.93	38.61
Days (exp. 6323)						
	116.18	99.30	90.28	90.28	90.98	91.34
Days (exp. 6335)						
	125.56	102.88	97.30	99.78	97.60	105.88
Days (exp. 6323, 6335)						
	120.87	101.09	93.79	95.03	94.29	98.61

Table 30. Combined experiments 6323, 6335 - analysis of variance plan and observed mean squares for average daily gain, feed required per pound of gain, percent ham and loin, and days required over the production period

Source of variation	d.f.	A.D.G.	F/G	Ham and loin (%)	Days
Replication	9	.0236**	.1307**	4.2706**	157.64**
Season	1	.1837**	.8401**	24.3462**	1068.50**
Rep./season	8	.0036	.0420	1.7611**	43.78
Protein level	5	.3554**	1.2647**	10.2409**	1064.58**
Linear	1	.8547**	2.7859**	43.1024**	2431.40**
Quadratic	1	.7924**	2.4022**	4.9312**	2563.41**
Cubic	1	.1052**	1.0063**	2.5916*	261.90*
Remainder	2	.0124	.0645	.2898	33.09
Rep. x protein level	45	.0051	.0346	.5847	43.97
Season x prot. level	5	.0080	.0277	.3023	34.08
Rep./season x prot. level	40	.0048	.0354	.6200	45.20
Total	59				

Table 31. Experiment 6323 - analysis of variance plan and observed mean squares for regression functions fitted to the body weight gain observations[a]

Source of variation	d.f.[b]	Square root	Quadratic
Regression	5	89003.03**	88808.27**
Error	211	12.96	17.57
Total	216		

[a]Functions correspond to equations 1.1 and 1.2.

[b]Error d.f. reduced to 25 (Tables 31, 32, 33, 34) and 55 (Tables 35, 36) for tests of significance, due to presence of autocorrelation.

Table 32. Experiment 6323 - correlation coefficients, standard errors of the regression coefficients and "t" values for the gain functions

Item	Square root	Quadratic
R^2	.993892	.991718
R	.996942	.995850
s.e.		
b_1	.013531	.008415
b_2	.053361	.033086
b_3	.308767	.000015
b_4	.508399	.000272
b_5	.046780	.000116

Table 32. (continued)

Item	Square root	Quadratic
t		
b_1	4.7773**	33.1224**
b_2	12.3910**	21.0744**
b_3	5.0257**	8.8083**
b_4	8.4715**	15.2884**
b_5	14.0135**	7.2467**

Table 33. Experiment 6335 - analysis of variance plan and observed mean squares for regression functions fitted to the body weight gain observations[a]

Source of variation	d.f.	Square root	Quadratic
Regression	5	92577.72**	92242.51**
Error	221	23.85	31.43
Total	226		

[a]Functions correspond to equations 1.3 and 1.4.

Table 34. Experiment 6335 - correlation coefficients, standard errors of the regression coefficients and "t" values for the gain functions

Item	Square root	Quadratic
R^2	.988741	.985161
R	.994355	.992553
s.e.		
b_1	.017535	.010305
b_2	.068159	.039031
b_3	.390506	.000018
b_4	.634735	.000314
b_5	.060113	.000137
t		
b_1	4.6854**	25.3839**
b_2	9.3267**	17.7367**
b_3	2.9895**	5.8215**
b_4	8.8386**	11.0966**
b_5	9.1298**	4.2325**

Table 35. Combined experiments 6323, 6335 - analysis of variance plan and observed mean squares for the regression functions fitted to the body weight gain observations[a]

Source of variation	d.f.	Square root	Quadratic
Regression	5	181128.97**	180850.63**
Error	438	24.70	27.88
Total	443		

[a]Functions correspond to equations 1.5 and 1.6.

Table 36. Combined experiments 6323, 6335 - correlation coefficients, standard errors of the regression coefficients and "t" values for the gain functions

Item	Square root	Quadratic
R^2	.988191	.986672
R	.994078	.993314
s.e.		
b_1	.012884	.007122
b_2	.049021	.025728
b_3	.290734	.000013
b_4	.464925	.000202
b_5	.044266	.000096
t		
b_1	5.1062**	38.2483**
b_2	14.9355**	27.5499**
b_3	5.0523**	9.6487**
b_4	12.3329**	19.0335**
b_5	13.9439**	6.9936**

Table 37. Experiment 6323 - total gain[a] (lb.)[b] resulting from incremental feed inputs of 50 pounds

Feed (lb.)	Percent protein										
	10	11	12	13	14	15	16	17	18	19	20
50	12.12	14.34	15.92	17.13	18.06	18.78	19.33	19.74	20.03	20.22	20.32
100	26.95	30.51	32.98	34.80	36.14	37.10	37.77	38.19	38.41	38.45	38.32
150	40.18	44.94	48.19	50.52	52.17	53.30	54.02	54.40	54.48	54.31	53.90
200	52.59	58.48	62.44	65.23	67.15	68.40	69.14	69.44	69.36	68.95	68.23
250	64.46	71.42	76.29	79.68	81.99	83.47	84.29	84.58	84.39	83.80	82.84
300	75.48	83.98	89.55	93.37	95.93	97.51	98.32	98.51	98.13	97.29	96.01
350	86.63	96.24	102.48	106.71	109.50	111.17	111.97	112.04	111.47	110.35	108.74
400	97.58	108.25	115.14	119.78	122.79	124.54	125.31	125.25	124.47	123.08	121.14
450	108.34	120.06	127.59	132.62	135.84	137.66	138.39	138.20	137.21	135.54	133.26
500	119.94	131.70	139.87	145.28	148.70	150.58	151.26	150.93	149.73	147.77	145.14
550	129.40	143.21	152.00	157.77	161.39	163.32	163.96	163.48	162.06	159.81	156.82
600	139.77	154.58									
650	150.04										
700	160.20										

[a]Derived from the square root gain function (equation 1.1).

[b]Beyond 50 lb. initial body weight.

Table 38. Experiment 6323 - marginal feed productivities for incremental inputs of 50 pounds

Feed (lb.)	Percent protein 10	11	12	13	14	15	16	17	18	19	20
50	.2424	.2868	.3184	.3426	.3612	.3756	.3866	.3948	.4006	.4044	.4064
100	.2966	.3234	.3412	.3534	.3616	.3664	.3688	.3690	.3676	.3646	.3600
150	.2646	.2886	.3042	.3144	.3206	.3240	.3250	.3242	.3214	.3172	.3116
200	.2482	.2708	.2850	.2942	.2996	.3020	.3024	.3008	.2976	.2928	.2866
250	.2374	.2594	.2736	.2830	.2882	.2908	.2910	.2892	.2858	.2810	.2748
300	.2286	.2512	.2652	.2738	.2788	.2808	.2806	.2786	.2748	.2698	.2634
350	.2230	.2452	.2586	.2668	.2714	.2732	.2730	.2706	.2668	.2612	.2546
400	.2190	.2402	.2532	.2614	.2658	.2674	.2668	.2642	.2600	.2546	.2480
450	.2152	.2362	.2490	.2568	.2610	.2624	.2616	.2590	.2548	.2492	.2424
500	.2320	.2328	.2456	.2532	.2572	.2584	.2574	.2546	.2504	.2446	.2376
550	.1892	.2302	.2426	.2498	.2538	.2548	.2540	.2510	.2466	.2408	.2336
600	.2074	.2274									
650	.2054										
700	.2032										

Table 39. Experiment 6323 - marginal productivity[a] of feed averaged over gain intervals

Percent protein	Gain intervals (lb.)						
	0-15	15-35	35-55	55-75	75-100	100-125	125-155
10	.2602	.2889	.2559	.2239	.2233	.2149	.2087
11	.2961	.3239	.2853	.2548	.2494	.2396	.2323
12	.3231	.3482	.3049	.2746	.2659	.2550	.2469
13	.3445	.3657	.3183	.2881	.2766	.2648	.2559
14	.3617	.3783	.3272	.2968	.2831	.2705	.2609
15	.3756	.3867	.3324	.3020	.2862	.2729	.2628
16	.3868	.3919	.3348	.3043	.2867	.2727	.2621
17	.3957	.3946	.3347	.3042	.2849	.2703	.2593
18	.4025	.3948	.3324	.3020	.2810	.2659	.2546
19	.4076	.3928	.3280	.2978	.2754	.2599	.2482
20	.4110	.3888	.3219	.2921	.2682	.2522	.2403

[a]Calculated from the feed quantities predicted over the intervals by the square root gain function (equation 1.1).

Table 40. Experiment 6335 - total gain[a] (lb.)[b] resulting from incremental feed inputs of 50 pounds

Feed (lb.)	Percent protein 10	11	12	13	14	15	16	17	18	19	20
50	10.48	12.98	14.79	16.23	17.37	18.29	19.05	19.65	20.14	20.52	20.82
100	24.82	28.62	31.33	33.37	34.93	36.11	37.00	37.66	38.11	38.39	38.50
150	37.65	42.57	45.99	48.51	50.36	51.69	52.63	53.25	53.57	53.66	53.51
200	49.70	55.64	59.69	62.62	64.69	66.13	67.06	67.58	67.74	67.59	67.15
250	61.24	68.09	72.96	76.39	78.80	80.40	81.39	81.87	81.90	81.55	80.87
300	71.96	80.22	85.67	89.45	92.04	93.70	94.64	94.99	94.82	94.20	93.19
350	82.83	92.04	98.05	102.16	104.91	106.60	107.48	107.68	107.29	106.38	105.03
400	93.50	103.62	110.16	114.58	117.48	119.19	119.99	120.03	119.40	118.21	116.50
450	104.01	115.00	122.06	126.78	129.80	131.53	132.23	132.10	131.22	129.73	127.67
500	114.35	126.22	133.79	138.78	141.92	143.64	144.25	143.93	142.81	141.00	138.58
550	124.57	137.31	145.36	150.62	153.87	155.57	156.08	155.57	154.19	152.06	149.26
600	134.70	148.27	156.80	162.31							159.76
650	144.74	159.12									
700	154.68										

[a]Derived from the square root gain function (equation 1.3).

[b]Beyond 50 lb. initial body weight.

Table 41. Experiment 6335 - marginal feed productivities for incremental inputs of 50 pounds

Feed (lb.)	Percent protein										
	10	11	12	13	14	15	16	17	18	19	20
50	.2096	.2596	.2958	.3246	.3474	.3658	.3810	.3930	.4028	.4104	.4164
100	.2868	.3128	.3308	.3428	.3512	.3564	.3590	.3602	.3594	.3574	.3536
150	.2566	.2790	.2932	.3028	.3086	.3116	.3126	.3118	.3092	.3054	.3002
200	.2410	.2614	.2740	.2822	.2866	.2888	.2886	.2866	.2834	.2786	.2728
250	.2308	.2504	.2628	.2706	.2748	.2764	.2760	.2738	.2700	.2650	.2592
300	.2228	.2426	.2542	.2612	.2648	.2660	.2650	.2624	.2584	.2530	.2464
350	.2174	.2364	.2476	.2542	.2574	.2580	.2568	.2538	.2494	.2436	.2368
400	.2134	.2316	.2422	.2484	.2514	.2518	.2502	.2470	.2422	.2366	.2294
450	.2102	.2276	.2380	.2440	.2464	.2468	.2468	.2414	.2364	.2304	.2234
500	.2068	.2244	.2346	.2400	.2424	.2422	.2404	.2366	.2318	.2254	.2182
550	.2044	.2218	.2314	.2368	.2390	.2386	.2366	.2328	.2276	.2212	.2136
600	.2026	.2192	.2288	.2338							.2100
650	.2008	.2170									
700	.1988										

Table 42. Experiment 6335 - marginal productivity[a] of feed averaged over gain intervals

Percent protein	Gain intervals (lb.)						
	0-15	15-35	35-55	55-75	75-100	100-125	125-155
10	.2367	.2751	.2456	.2158	.2163	.2087	.2030
11	.2743	.3088	.2725	.2433	.2387	.2295	.2225
12	.3038	.3328	.2907	.2610	.2528	.2422	.2341
13	.3284	.3508	.3035	.2730	.2618	.2499	.2409
14	.3592	.3643	.3121	.2807	.2669	.2539	.2441
15	.3667	.3743	.3174	.2852	.2690	.2550	.2446
16	.3819	.3811	.3201	.2872	.2688	.2539	.2428
17	.3948	.3857	.3205	.2869	.2664	.2507	.2389
18	.4061	.3879	.3189	.2846	.2623	.2457	.2334
19	.4156	.3881	.3155	.2805	.2565	.2392	.2264
20	.4237	.3865	.3103	.2750	.2492	.2313	.2180

[a]Calculated from the feed quantities predicted over the intervals by the square root gain function (equation 1.3).

Table 43. Experiment 6323 - corn and soybean meal quantities[a] (lb.) and substitution rates[b] of soybean meal for corn (MRS)[c] at gain contours[d]

Percent protein	15 lb. gain contour			35 lb. gain contour			55 lb. gain contour		
	Corn	SBM	MRS	Corn	SBM	MRS	Corn	SBM	MRS
10	55.41	2.24	10.24	121.94	4.94	9.64	197.07	7.98	9.31
11	47.47	3.19	6.90	105.32	7.08	6.27	171.00	11.49	5.93
12	42.39	4.04	5.16	94.83	9.04	4.55	154.72	14.75	4.21
13	38.69	4.85	4.07	87.29	10.94	3.47	143.12	17.94	3.15
14	35.84	5.63	3.31	81.54	12.80	2.74	134.37	21.10	2.43
15	33.56	6.38	2.76	77.02	14.64	2.21	127.56	24.26	1.91
16	31.65	7.13	2.33	73.30	16.51	1.80	122.05	27.49	1.52
17	30.03	7.88	1.99	70.18	18.42	1.48	117.51	30.84	1.20
18	28.62	8.65	1.71	67.53	20.40	1.21	113.74	34.36	.95
19	27.37	9.43	1.48	65.23	22.48	.99	110.58	38.11	.74
20	26.26	10.24	1.27	63.26	24.68	.81	107.96	42.12	.57

[a]Derived from the square root gain function (equation 1.1).

[b]Calculated by use of equation 2.1.

[c]The negative signs have been omitted from the substitution rates, here and throughout the appendix.

[d]All gain contours relate to an initial body weight of 50 lb.

Table 43. (continued)

Percent protein	75 lb. gain contour			100 lb. gain contour		
	Corn	SBM	MRS	Corn	SBM	MRS
10	283.79	10.57	9.77	391.73	14.60	9.58
11	245.41	15.58	6.02	339.68	21.57	5.83
12	222.06	20.23	4.19	308.23	28.08	4.00
13	205.70	24.78	3.08	286.35	34.50	2.90
14	193.53	29.32	2.33	270.22	40.93	2.16
15	184.17	33.87	1.80	257.95	47.44	1.64
16	176.71	38.56	1.40	248.29	54.17	1.25
17	170.60	43.49	1.09	240.53	61.32	.94
18	165.64	48.69	.83	234.39	68.90	.69
19	161.67	54.17	.63	229.66	76.95	.49
20	158.51	60.05	.46	226.12	85.66	.33

Table 43. (continued)

Percent protein	125 lb. gain contour			155 lb. gain contour		
	Corn	SBM	MRS	Corn	SBM	MRS
10	503.86	18.78	9.44	642.48	23.94	9.32
11	437.78	27.80	5.69	559.23	35.51	5.56
12	398.07	36.26	3.86	509.45	46.41	3.74
13	370.60	44.65	2.77	475.22	57.25	2.65
14	350.49	53.09	2.04	450.34	68.22	1.93
15	353.34	61.67	1.52	431.76	79.40	1.42
16	323.54	70.59	1.14	417.48	91.09	1.04
17	314.23	80.11	.83	406.42	103.61	.74
18	307.05	90.26	.59	398.11	117.03	.51
19	301.72	101.09	.40	392.26	131.42	.32
20	298.01	112.89	.24	388.56	147.19	.16

Table 44. Experiment 6335 - corn and soybean meal quantities[a] (lb.) and substitution rates[b] of soybean meal for corn (MRS) at gain contours[c]

Percent protein	15 lb. gain contour			35 lb. gain contour			55 lb. gain contour		
	Corn	SBM	MRS	Corn	SBM	MRS	Corn	SBM	MRS
10	60.89	2.47	11.85	130.77	5.30	10.33	209.03	8.46	9.52
11	51.24	3.44	8.24	111.94	7.52	6.93	180.69	12.15	6.24
12	45.08	4.30	6.33	99.94	9.53	5.16	162.74	15.52	4.54
13	40.59	5.09	5.10	91.25	11.44	4.03	149.81	18.78	3.47
14	37.13	5.83	4.25	84.58	13.28	3.25	139.97	21.98	2.73
15	34.37	6.54	3.62	79.28	15.07	2.68	132.23	25.14	2.19
16	32.06	7.22	3.13	74.89	16.87	2.24	125.89	28.36	1.77
17	30.09	7.90	2.73	71.17	18.68	1.88	120.60	31.65	1.44
18	28.37	8.57	2.40	67.97	20.53	1.59	116.14	35.08	1.17
19	26.84	9.25	2.12	65.16	22.46	1.34	112.31	38.70	.95
20	25.47	9.93	1.88	62.69	24.45	1.13	109.05	42.54	.76

[a]Derived from the square root gain function (equation 1.3).

[b]Calculated by use of equation 2.2.

[c]All gain contours relate to an initial body weight of 50 lb.

Table 44. (continued)

Percent protein	75 lb. gain contour			100 lb. gain contour		
	Corn	SBM	MRS	Corn	SBM	MRS
10	299.03	11.14	9.63	410.47	15.30	9.17
11	258.61	16.42	6.11	357.08	22.67	5.72
12	233.60	21.28	4.34	324.23	29.53	4.00
13	215.85	26.00	3.25	301.09	36.27	2.94
14	202.51	30.68	2.50	283.87	43.00	2.22
15	192.15	35.34	1.97	270.65	49.77	1.71
16	183.80	40.10	1.56	260.15	56.76	1.31
17	176.88	45.09	1.23	251.65	64.15	1.00
18	171.17	50.32	.96	244.84	71.97	.75
19	166.51	55.79	.75	239.53	80.25	.54
20	162.70	61.63	.56	235.47	89.20	.37

Table 44. (continued)

Percent protein	125 lb. gain contour			155 lb. gain contour		
	Corn	SBM	MRS	Corn	SBM	MRS
10	525.94	19.60	8.84	668.43	24.91	8.55
11	459.51	29.18	5.45	586.29	37.23	5.21
12	418.84	38.15	3.76	536.27	48.85	3.55
13	390.38	47.03	2.72	501.51	60.42	2.53
14	369.37	55.95	2.03	476.09	72.12	1.85
15	353.44	65.00	1.53	457.05	84.05	1.37
16	340.98	74.40	1.14	442.43	96.53	1.00
17	331.10	84.41	.84	431.14	109.92	.70
18	323.46	95.08	.60	422.78	124.28	.47
19	317.80	106.48	.40	417.05	139.73	.28
20	313.87	118.90	.24	413.68	156.71	.12

Table 45. Combined experiments 6323, 6335 - corn and soybean meal quantities[a] (lb.) and substitution rates[b] of soybean meal for corn (MRS) at gain contours[c]

Percent protein	15 lb. gain contour			35 lb. gain contour			55 lb. gain contour		
	Corn	SBM	MRS	Corn	SBM	MRS	Corn	SBM	MRS
10	60.54	2.45	11.84	127.70	5.17	10.69	203.77	8.25	10.03
11	51.00	3.43	8.07	109.02	7.33	7.02	175.38	11.79	6.43
12	44.97	4.29	6.10	97.31	9.28	5.13	157.73	15.04	4.58
13	40.60	5.09	4.86	88.92	11.14	3.95	145.18	18.20	3.44
14	37.26	5.85	4.00	82.53	12.96	3.14	135.75	21.31	2.66
15	34.59	6.58	3.36	77.50	14.74	2.55	128.41	24.42	2.10
16	32.37	7.29	2.87	73.37	16.53	2.09	122.48	27.59	1.67
17	30.48	8.00	2.48	69.91	18.35	1.73	117.61	30.87	1.32
18	28.84	8.71	2.15	66.95	20.22	1.44	113.56	34.30	1.05
19	27.38	9.44	1.88	64.38	22.19	1.19	110.16	37.96	.82
20	26.08	10.17	1.64	62.16	24.25	.98	107.35	41.88	.62

[a]Derived from the square root gain function (equation 1.5).

[b]Calculated by use of equation 2.3.

[c]All gain contours relate to an initial body weight of 50 lb.

Table 45. (continued)

Percent protein	75 lb. gain contour			100 lb. gain contour		
	Corn	SBM	MRS	Corn	SBM	MRS
10	292.27	10.89	10.31	402.41	14.99	9.92
11	251.25	15.95	6.37	347.67	22.08	6.03
12	226.40	20.62	4.44	314.75	28.67	4.12
13	209.05	25.18	3.26	291.97	35.17	2.97
14	196.19	29.72	2.46	275.29	41.70	2.19
15	186.35	34.27	1.89	262.71	48.31	1.64
16	178.53	38.95	1.46	252.92	55.19	1.23
17	172.18	43.90	1.12	245.19	62.51	.90
18	167.07	49.11	.85	239.23	70.32	.64
19	163.03	54.62	.63	234.83	78.68	.42
20	159.89	60.57	.44	231.79	87.81	.25

Table 45. (continued)

Percent protein	125 lb. gain contour			155 lb. gain contour		
	Corn	SBM	MRS	Corn	SBM	MRS
10	517.18	19.27	9.64	659.46	24.57	9.39
11	448.47	28.48	5.78	573.78	36.43	5.55
12	407.43	37.11	3.90	522.95	47.63	3.69
13	379.25	45.69	2.76	488.33	58.83	2.57
14	358.83	54.36	2.00	463.53	70.22	1.83
15	343.65	63.20	1.46	445.37	81.90	1.31
16	332.06	72.45	1.06	431.83	94.22	.91
17	323.18	82.39	.74	421.84	107.54	.60
18	316.66	93.09	.49	414.97	121.99	.36
19	312.26	104.62	.28	410.96	137.69	.16
20	309.77	117.35	.11	409.63	155.18	+.002

Table 46. Experiment 6323 - corn and soybean meal quantities[a] (lb.) and substitution rates[b] of soybean meal for corn (MRS) over gain intervals[c]

Percent protein	0 to 15 lb. of gain			15 to 35 lb. of gain			35 to 55 lb. of gain		
	Corn	SBM	MRS	Corn	SBM	MRS	Corn	SBM	MRS
10	55.41	2.24	10.24	66.53	2.70	9.22	75.13	3.04	8.84
11	47.47	3.19	6.90	57.85	3.89	5.88	65.68	4.41	5.50
12	42.39	4.04	5.16	52.44	5.00	4.22	59.89	5.71	3.82
13	38.69	4.85	4.07	48.60	6.09	3.18	55.83	7.00	2.81
14	35.84	5.63	3.31	45.70	7.17	2.49	52.83	8.30	2.12
15	33.56	6.38	2.76	43.46	8.26	1.99	50.54	9.62	1.64
16	31.65	7.13	2.33	41.65	9.38	1.61	48.75	10.98	1.28
17	30.03	7.88	1.99	40.15	10.54	1.31	47.33	12.42	.99
18	28.62	8.65	1.71	38.91	11.75	1.06	46.21	13.96	.77
19	27.37	9.43	1.48	37.86	13.05	.86	45.35	15.63	.58
20	26.26	10.24	1.27	37.00	14.44	.70	44.70	17.44	.43

[a]Calculated from quantities derived from the square root gain function (equation 1.1).

[b]Calculated by use of equation 2.4.

[c]Gain intervals relate to an initial body weight of 50 lb.

Table 46. (continued)

Percent protein	55 to 75 lb. of gain			75 to 100 lb. gain		
	Corn	SBM	MRS	Corn	SBM	MRS
10	86.72	2.59	10.92	107.94	4.03	9.13
11	74.41	4.09	6.22	94.27	5.99	5.42
12	67.34	5.48	4.15	86.17	7.85	3.62
13	62.58	6.84	2.95	80.65	9.72	2.56
14	59.16	8.22	2.16	76.69	11.61	1.86
15	56.61	9.61	1.62	73.78	13.57	1.38
16	54.66	11.07	1.22	71.58	15.61	1.02
17	53.09	12.65	.93	69.93	17.83	.73
18	51.90	14.33	.67	68.75	20.21	.51
19	51.09	16.06	.50	67.99	22.78	.34
20	50.55	17.93	.34	67.61	25.61	.21

Table 46. (continued)

Percent protein	100 to 125 lb. of gain			125 to 155 lb. of gain		
	Corn	SBM	MRS	Corn	SBM	MRS
10	112.13	4.18	8.99	138.62	5.16	8.92
11	98.10	6.23	5.27	121.45	7.71	5.16
12	89.84	8.18	3.48	111.38	10.15	3.39
13	84.25	10.15	2.43	104.62	12.60	2.32
14	80.27	12.16	1.75	99.85	15.13	1.65
15	77.39	14.23	1.25	96.42	17.73	1.18
16	75.25	16.42	.91	93.94	20.50	.82
17	73.70	18.79	.62	92.19	23.50	.56
18	72.66	21.36	.42	91.06	26.77	.36
19	72.06	24.14	.27	90.54	30.33	.20
20	71.89	27.23	.14	90.55	34.30	.08

Table 47. Experiment 6335 - corn and soybean meal quantities[a] (lb.) and substitution rates[b] of soybean meal for corn (MRS) over gain intervals[c]

Percent protein	0 to 15 lb. of gain			15 to 35 lb. of gain			35 to 55 lb. of gain		
	Corn	SBM	MRS	Corn	SBM	MRS	Corn	SBM	MRS
10	60.89	2.47	11.85	69.88	2.83	9.47	78.26	3.16	8.55
11	51.24	3.44	8.24	60.69	4.08	6.31	68.76	4.63	5.51
12	45.08	4.30	6.33	54.86	5.23	4.69	62.80	5.99	3.96
13	40.59	5.09	5.10	50.66	6.35	3.66	58.56	7.34	2.99
14	37.13	5.83	4.25	47.45	7.45	2.96	55.39	8.70	2.33
15	34.37	6.54	3.62	44.91	8.53	2.44	52.95	10.07	1.85
16	32.06	7.22	3.13	42.83	9.65	2.04	51.00	11.49	1.47
17	30.09	7.90	2.73	41.08	10.78	1.71	49.43	12.97	1.18
18	28.37	8.57	2.40	39.60	11.96	1.45	48.17	14.55	.95
19	26.84	9.25	2.12	38.32	13.21	1.22	47.15	16.24	.76
20	25.47	9.93	1.88	37.22	14.52	1.03	46.36	18.09	.60

[a]Calculated from quantities derived from the square root gain function (equation 1.3).

[b]Calculated by use of equation 2.4.

[c]Gain intervals relate to an initial body weight of 50 lb.

Table 47. (continued)

Percent protein	55 to 75 lb. of gain			75 to 100 lb. gain		
	Corn	SBM	MRS	Corn	SBM	MRS
10	90.00	2.68	9.87	111.44	4.16	8.21
11	77.92	4.27	5.87	98.47	6.25	4.99
12	70.86	5.76	4.01	90.63	8.25	3.42
13	66.04	7.22	2.91	85.24	10.27	2.45
14	62.54	8.70	2.18	81.36	12.32	1.81
15	59.92	10.20	1.68	78.50	14.43	1.36
16	57.91	11.74	1.30	76.35	16.66	1.01
17	56.28	13.44	1.00	74.77	19.06	.74
18	55.03	15.24	.75	73.67	21.65	.54
19	54.20	17.09	.57	73.02	24.46	.36
20	53.65	19.09	.40	72.77	27.57	.23

Table 47. (continued)

Percent protein	100 to 125 lb. of gain			125 to 155 lb. of gain		
	Corn	SBM	MRS	Corn	SBM	MRS
10	115.47	4.30	7.90	142.49	5.31	7.69
11	102.43	6.51	4.75	126.78	8.05	4.55
12	94.61	8.62	3.19	117.43	10.70	3.02
13	89.29	10.76	2.24	111.13	13.39	2.09
14	85.50	12.95	1.64	106.72	16.17	1.47
15	82.79	15.23	1.19	103.61	19.05	1.05
16	80.83	17.64	.85	101.45	22.13	.74
17	79.45	20.26	.59	100.04	25.51	.48
18	78.62	23.11	.40	99.32	29.20	.30
19	78.27	26.23	.24	99.25	33.25	.16
20	78.40	29.70	.13	99.81	37.81	.05

Table 48. Combined experiments 6323, 6335 - corn and soybean meal quantities[a] (lb.) and substitution rates[b] of soybean meal for corn (MRS) over gain intervals[c]

Percent protein	0 to 15 lb. of gain			15 to 35 lb. of gain			35 to 55 lb. of gain		
	Corn	SBM	MRS	Corn	SBM	MRS	Corn	SBM	MRS
10	60.54	2.45	11.84	67.16	2.72	9.93	76.07	3.08	9.19
11	51.00	3.43	8.07	58.02	3.90	6.45	66.36	4.46	5.76
12	44.97	4.29	6.10	52.34	4.99	4.68	60.42	5.76	4.03
13	40.60	5.09	4.86	48.32	6.05	3.58	56.26	7.06	2.98
14	37.26	5.85	4.00	45.27	7.11	2.84	53.22	8.35	2.27
15	34.59	6.58	3.36	42.91	8.16	2.30	50.91	9.68	1.77
16	32.37	7.29	2.87	41.00	9.24	1.88	49.11	11.06	1.38
17	30.48	8.00	2.48	39.43	10.35	1.55	47.70	12.52	1.07
18	28.84	8.71	2.15	38.11	11.51	1.29	46.61	14.08	.83
19	27.38	9.44	1.88	37.00	12.75	1.06	45.78	15.77	.64
20	26.08	10.17	1.64	36.08	14.08	.87	45.19	17.63	.47

[a] Calculated from quantities derived from the square root gain function (equation 1.5).

[b] Calculated by use of equation 2.4.

[c] Gain intervals relate to an initial body weight of 50 lb.

Table 48. (continued)

Percent protein	55 to 75 lb. of gain			75 to 100 lb. gain		
	Corn	SBM	MRS	Corn	SBM	MRS
10	88.50	2.64	10.94	110.14	4.10	9.08
11	75.87	4.16	6.26	96.42	6.13	5.37
12	68.67	5.58	4.19	88.35	8.05	3.56
13	63.87	6.98	2.97	82.92	9.99	2.50
14	60.44	8.41	2.17	79.10	11.98	1.79
15	57.94	9.85	1.61	76.36	14.04	1.30
16	56.05	11.36	1.20	74.39	16.24	.94
17	54.57	13.03	.89	73.01	18.61	.66
18	53.51	14.81	.65	72.16	21.21	.44
19	52.87	16.66	.46	71.80	24.06	.26
20	52.54	18.69	.30	71.90	27.24	.14

Table 48. (continued)

Percent protein	100 to 125 lb. of gain			125 to 155 lb. of gain		
	Corn	SBM	MRS	Corn	SBM	MRS
10	114.77	4.28	8.83	142.28	5.30	8.63
11	100.80	6.40	5.12	125.31	7.95	4.92
12	92.68	8.44	3.37	115.52	10.52	3.16
13	87.28	10.52	2.30	109.08	13.14	2.13
14	83.54	12.66	1.61	104.70	15.86	1.46
15	80.94	14.89	1.13	101.72	18.70	1.01
16	79.14	17.26	.78	99.77	21.77	.65
17	77.99	19.88	.51	98.66	25.15	.39
18	77.43	22.77	.31	98.31	28.90	.21
19	77.43	25.94	.15	98.70	33.07	.07
20	77.98	29.54	.05	99.86	37.83	+.0005

Table 49. Experiment 6323 - analysis of variance plan and observed mean squares (m.s.) for several regression functions[a] fitted to the percent ham and loin observations

Source of variation	Linear d.f.	Linear m.s.	Linear with interaction d.f.	Linear with interaction m.s.	Quadratic without interaction d.f.	Quadratic without interaction m.s.	Square root without interaction d.f.	Square root without interaction m.s.	Quadratic 1.5 power without interaction d.f.	Quadratic 1.5 power without interaction m.s.	Quadratic ratio d.f.	Quadratic ratio m.s.
Regression	2	11.9909**	3	8.1778**	4	6.3791**	4	6.4612**	4	6.3900**	5	5.1448**
Error	27	.8794	26	.8920	25	.8884	25	.8752	25	.8866	24	.9167
Total	29		29		29		29		29		29	

[a]Functions correspond to equations 3.1, 3.2, 3.3, 3.4, 3.5 and 3.6.

Table 50. Experiment 6323 - correlation coefficients, standard errors of the regression coefficients and "t" values[a] for the functions fitted to the percent ham and loin observations

Item	Linear	Linear with interaction	Quadratic without interaction	Square root without interaction	Quadratic 1.5 power without interaction	Quadratic ratio
R^2	.502498	.514055	.534648	.541535	.535569	.539001
R	.708871	.716976	.731196	.735890	.731826	.734167
s.e.						
b_1	.004299	.004866	.035115	.069778	.069416	.099276
b_2	.007466	.033116	.032399	.047988	.059028	.068620
b_3			.000035	3.033402	.002084	.000087
b_4			.000159	.910376	.003969	.000257
b_5		.000083				42.750672
t						
b_1	3.2320	2.4965	1.6987	1.2546	1.5311	1.0439
b_2	.5442	.6431	.1532	.9431	.3959	.4889
b_3			1.3019	1.4595	1.3289	.9554
b_4			.4237	.7919	.5390	.1061
b_5		.7863				.4747

[a]Statistical significance indicated in Table 55.

Table 51. Experiment 6335 - analysis of variance plan and observed mean squares (m.s.) for several regression functions[a] fitted to the percent ham and loin observations

Source of variation	Linear		Linear with interaction		Quadratic without interaction		Square root without interaction		Quadratic 1.5 power without interaction		Quadratic ratio	
	d.f.	m.s.	d.f.	m.s.	d.f.	m.s.	d.f.	m.s.	d.f.	m.s.	d.f.	m.s.
Regression	2	14.4314**	3	9.8425**	4	7.5137**	4	7.5353**	4	7.5239**	5	6.0585**
Error	27	.5561	26	.5520	25	.5529	25	.5495	25	.5513	24	.5661
Total	29		29		29		29		29		29	

[a]Functions correspond to equations 4.1, 4.2, 4.3, 4.4, 4.5 and 4.6.

Table 52. Experiment 6335 - correlation coefficients, standard errors of the regression coefficients[a] and "t" values for the functions fitted to the percent ham and loin observations

Item	Linear	Linear with interaction	Quadratic without interaction	Square root without interaction	Quadratic 1.5 power without interaction	Quadratic ratio
R^2	.657791	.672943	.684955	.686930	.685891	.690379
R	.811043	.820331	.827620	.828812	.828185	.830890
s.e.						
b_1	.003590	.004201	.037261	.081730	.075673	.117300
b_2	.005478	.025097	.020704	.032474	.037417	.071710
b_3			.000035	3.689815	.002213	.000100
b_4			.000095	.615550	.002446	.000155
b_5		.000056				44.247957
t						
b_1	2.6475	2.8383	.0929	.0533	.0781	.6464
b_2	1.3007	.7872	1.5430	.8969	1.4120	.1776
b_3			.2602	.0159	.1571	.7004
b_4			1.1392	1.2091	1.1768	1.2071
b_5		1.0974				.6515

[a]Statistical significance indicated in Table 55.

Table 53. Combined experiments 6323, 6335 - analysis of variance plan and observed mean squares (m.s.) for several regression functions[a] fitted to the percent ham and loin observations

Source of variation	Linear		Linear with interaction		Quadratic without interaction		Square root without interaction		Quadratic 1.5 power without interaction		Quadratic ratio	
	d.f.	m.s.	d.f.	m.s.	d.f.	m.s.	d.f.	m.s.	d.f.	m.s.	d.f.	m.s.
Regression	2	22.5002**	3	16.8356**	4	12.3152**	4	12.6763**	4	12.4229**	5	10.0030**
Error	57	1.2447	56	1.1686	55	1.2125	55	1.1863	55	1.2047	54	1.2210
Total	59		59		59		59		59		59	

[a]Functions correspond to equations 5.1, 5.2, 5.3, 5.4, 5.5 and 5.6.

Table 54. Combined experiments 6323, 6335 - correlation coefficients, standard errors of the regression coefficients[a] and "t" values for the functions fitted to the percent ham and loin observations

Item	Linear	Linear with interaction	Quadratic without interaction	Square root without interaction	Quadratic 1.5 power without interaction	Quadratic ratio
R^2	.388103	.435591	.424845	.437303	.428562	.431352
R	.622979	.659993	.651802	.661289	.654646	.656774
s.e.						
b_1	.003262	.004021	.027449	.056537	.054891	.077588
b_2	.005412	.024538	.022062	.032513	.039831	.052534
b_3			.000027	2.480553	.001643	.000068
b_4			.000104	.622461	.002628	.000139
b_5		.000056				30.013680
t						
b_1	.9059	2.0767	.9335	.3580	.7864	.4024
b_2	2.7739	1.5086	1.8407	1.0923	1.6817	1.4837
b_3			.9249	.3948	.7698	.3472
b_4			1.1114	1.6258	1.2718	.3086
b_5		2.1706				.7837

[a]Statistical significance indicated in Table 55.

Table 55. Individual and combined experiments 6323, 6335 - probability levels indicating significance of the regression coefficients[a] of the terms in the functions fitted to the percent ham and loin observations

Coefficient	Linear	Linear with interaction	Quadratic without interaction	Square root without interaction	Quadratic 1.5 power without interaction	Quadratic ratio
Exp. 6323						
b_1	.01	.01	.20	.40	.20	.40
b_2				.40		
b_3	---	---	.40	.20	.20	.40
b_4	---	---		.50		
b_5	---	.50	---	---	---	
Exp. 6335						
b_1	.01	.01				
b_2	.40	.50	.20	.40	.20	
b_3	---	---				.50
b_4	---	---	.40	.40	.40	.40
b_5	---	.40	---	---	---	

[a]Dash indicates that the specified coefficient is not contained in the function.

Table 55. (continued)

Coefficient	Linear	Linear with interaction	Quadratic without interaction	Square root without interaction	Quadratic 1.5 power without interaction	Quadratic ratio
Combined exp. 6323, 6335						
b_1	.40	.05	.40		.50	
b_2	.01	.20	.10	.40	.10	.20
b_3	---	---	.40		.50	
b_4	---	---	.40	.20	.40	
b_5	---	.05	---	---	---	.50

Table 56. Experiment 6323 - comparison of the observed ham and loin percent with the ham and loin percent predicted from several regression functions[a]

		Function					
Percent protein	Observed ham and loin (%)	Linear	Linear with interaction	Quadratic without interaction	Square root without interaction	Quadratic 1.5 power without interaction	Quadratic ratio
10	35.18	34.58	34.71	35.14	35.17	35.14	35.28
11		35.69	35.68	35.57	35.65	35.58	35.46
12	36.60	36.33	36.27	36.11	36.18	36.13	36.02
13		36.77	36.68	36.60	36.65	36.61	36.56
14	37.19	37.07	36.97	37.00	37.04	37.01	36.99
15		37.28	37.22	37.30	37.33	37.32	37.32
16	37.29	37.43	37.40	37.53	37.55	37.54	37.54
17		37.53	37.53	37.67	37.67	37.68	37.67
18	37.04	37.59	37.63	37.73	37.72	37.73	37.71
19		37.62	37.68	37.70	37.67	37.69	37.68
20	38.00	37.60	37.70	37.57	37.53	37.55	37.58

[a]Functions correspond to equations 3.1, 3.2, 3.3, 3.4, 3.5 and 3.6.

Table 57. Experiment 6323 - comparison of the increase in observed ham and loin percent with the increase[a] in ham and loin percent[b] predicted from the regression functions

Percent protein	Observed ham and loin)	Function					
		Linear	Linear with interaction	Quadratic without interaction	Square root without interaction	Quadratic 1.5 power without interaction	Quadratic ratio
10							
11		1.11	.97	.43	.48	.44	.18
12	1.42	.64	.59	.54	.53	.55	.56
13		.44	.41	.49	.47	.48	.54
14	.59	.30	.31	.40	.39	.40	.43
15		.21	.23	.30	.29	.31	.33
16	.10	.15	.18	.23	.22	.22	.22
17		.10	.13	.14	.12	.14	.13
18	-.25	.06	.10	.06	.05	.05	.04
19		.03	.05	-.03	-.05	-.04	-.03
20	.96	-.02	.02	-.13	-.14	-.14	-.10

[a]Values indicate an increase from one protein level to the next highest.

[b]Negative values indicate a decrease from one protein level to the next highest.

Table 58. Experiment 6335 - comparison of the observed ham and loin percent with the ham and loin percent predicted from several regression functions[a]

		Function					
Percent protein	Observed ham and loin (%)	Linear	Linear with interaction	Quadratic without interaction	Square root without interaction	Quadratic 1.5 power without interaction	Quadratic ratio
10	36.27	35.99	35.78	35.86	35.97	35.91	35.51
11		36.86	36.84	36.84	36.89	36.85	36.97
12	37.57	37.42	37.48	37.45	37.49	37.46	37.58
13		37.83	37.92	37.90	37.94	37.91	37.94
14	38.16	38.16	38.24	38.24	38.28	38.26	38.21
15		38.42	38.48	38.52	38.54	38.53	38.45
16	38.91	38.65	38.67	38.75	38.75	38.76	38.67
17		38.85	38.83	38.93	38.91	38.93	38.88
18	38.82	39.04	38.97	39.06	39.04	39.06	39.06
19		39.20	39.09	39.14	39.12	39.14	39.19
20	39.22	39.35	39.19	39.16	39.17	39.16	39.23

[a]Functions correspond to equations 4.1, 4.2, 4.3, 4.4, 4.5 and 4.6.

Table 59. Experiment 6335 - comparison of the increase[a] in observed ham and loin percent with the increase[b] in ham and loin percent predicted from the regression functions

Percent protein	Observed ham and loin	Function					
		Linear	Linear with interaction	Quadratic without interaction	Square root without interaction	Quadratic 1.5 power without interaction	Quadratic ratio
10							
11		.87	1.06	.98	.92	.94	1.46
12	1.30	.56	.64	.61	.60	.61	.61
13		.41	.44	.45	.45	.45	.36
14	.59	.33	.32	.34	.34	.35	.27
15		.26	.24	.28	.26	.27	.24
16	.75	.23	.19	.23	.21	.23	.22
17		.20	.16	.18	.16	.17	.21
18	-.09	.19	.14	.13	.13	.13	.18
19		.16	.12	.08	.08	.08	.13
20	.40	.15	.10	.02	.05	.02	.04

[a]Negative value indicates a decrease from 18 to 20 percent protein.

[b]Values indicate an increase from one protein level to the next highest.

Table 60. Combined experiments 6323, 6335 - comparison of the observed ham and loin percent with the ham and loin percent predicted from several regression functions[a]

Percent protein	Observed ham and loin (%)	Function					
		Linear	Linear with interaction	Quadratic without interaction	Square root without interaction	Quadratic 1.5 power without interaction	Quadratic ratio
10	35.72	36.02	35.57	35.59	35.79	35.66	35.87
11		36.45	36.41	36.46	36.50	36.46	36.33
12	37.09	36.77	36.90	36.91	36.95	36.91	36.78
13		37.04	37.24	37.22	37.27	37.23	37.17
14	37.67	37.28	37.48	37.47	37.53	37.49	37.48
15		37.51	37.68	37.69	37.75	37.71	37.73
16	38.10	37.74	37.84	37.90	37.93	37.91	37.93
17		37.97	38.00	38.08	38.09	38.10	38.10
18	37.93	38.20	38.15	38.26	38.24	38.26	38.24
19		38.45	38.33	38.41	38.36	38.39	38.37
20	38.61	38.72	38.53	38.52	38.47	38.50	38.50

[a]Functions correspond to equations 5.1, 5.2, 5.3, 5.4, 5.5 and 5.6.

Table 61. Combined experiments 6323, 6335 - comparison of the increase in observed ham and loin percent with the increase[a] in ham and loin percent predicted from the regression functions

Percent protein	Observed ham and loin	Function: Linear	Linear with interaction	Quadratic without interaction	Square root without interaction	Quadratic 1.5 power without interaction	Quadratic ratio
10							
11		.43	.84	.87	.71	.80	.46
12	1.37	.32	.49	.45	.45	.45	.45
13		.27	.34	.31	.32	.32	.39
14	.58	.24	.24	.25	.26	.26	.31
15		.23	.20	.22	.22	.22	.25
16	.43	.23	.16	.21	.18	.20	.20
17		.23	.16	.18	.16	.19	.17
18	-.17	.23	.15	.18	.15	.16	.14
19		.25	.18	.15	.12	.13	.13
20	.68	.27	.20	.11	.11	.11	.13

[a]Values indicate an increase from one protein level to the next highest.

Table 62. Experiment 6323 - analysis of variance plan and observed mean squares for the marginal time functions[a]

Source of variation	d.f.	Square root	Quadratic
Regression	5	.8663**	.8306**
Error	211	.0113	.0121
Total	216		

[a]Functions correspond to equations 6.1 and 6.2.

Table 63. Experiment 6323 - correlation coefficients, standard errors of the regression coefficients and "t" values for the marginal time functions[a]

Item	Square root	Quadratic
R^2	.645065	.618496
R	.803159	.786445
s.e.		
b_1	.042910	.022817
b_2	.001069	.000996
b_3	.323965	.000765
b_4	.027335	.000004
b_5	.006283	.000051

[a]Functions correspond to equations 6.1 and 6.2.

Table 63. (continued)

Item	Square root	Quadratic
t		
b_1	6.8344**	8.2551**
b_2	6.9243**	9.5236**
b_3	7.9155**	6.7439**
b_4	8.3161**	7.6704**
b_5	3.1329**	3.4094**

Table 64. Experiment 6335 - analysis of variance plan and observed mean squares for the marginal time functions[a]

Source of variation	d.f.	Square root	Quadratic
Regression	5	1.3033**	1.2452**
Error	221	.0150	.0163
Total	226		

[a]Functions correspond to equations 6.3 and 6.4.

Table 65. Experiment 6335 - correlation coefficients, standard errors of the regression coefficients and "t" values for marginal time functions[a]

Item	Square root	Quadratic
R^2	.663447	.633870
R	.814522	.796159
s.e.		
b_1	.048378	.025685
b_2	.001145	.001082
b_3	.363782	.000865
b_4	.029592	.000004
b_5	.007018	.000057
t		
b_1	7.0693**	8.4078**
b_2	6.5057**	11.3305**
b_3	8.3626**	6.9355**
b_4	10.2314**	8.1480**
b_5	5.2269**	4.5575**

[a]Functions correspond to equations 6.3 and 6.4.

Table 66. Combined experiments 6323, 6335 - analysis of variance plan and observed mean squares for the marginal time functions[a]

Source of variation	d.f.	Square root	Quadratic
Regression	5	2.1506**	2.0584**
Error	438	.0138	.0148
Total	443		

[a]Functions correspond to equations 6.5 and 6.6.

Table 67. Combined experiments 6323, 6335 - correlation coefficients, standard errors of the regression coefficients and "t" values for the marginal time functions[a]

Item	Square root	Quadratic
R^2	.640460	.613005
R	.800287	.782946
s.e.		
b_1	.033165	.017579
b_2	.000804	.000753
b_3	.249855	.000591
b_4	.020668	.000003
b_5	.004832	.000039
t		
b_1	9.6305**	11.5444**
b_2	9.2735**	14.5374**
b_3	11.2826**	9.4856**
b_4	12.9199**	11.0024**
b_5	5.8881**	5.5670**

[a]Functions correspond to equations 6.5 and 6.6.

Table 68. Experiment 6323 - marginal days[a] per pound of marginal gain over specified gain intervals[b]

Percent protein	Gain intervals (lb.)						
	0-15	15-35	35-55	55-75	75-100	100-125	125-155
10	1.1182	.9289	.8293	.7719	.7357	.7258	.7381
11	1.0275	.8444	.7493	.6957	.6635	.6572	.6735
12	.9538	.7766	.6859	.6359	.6076	.6048	.6247
13	.8951	.7236	.6370	.5905	.5660	.5664	.5898
14	.8497	.6837	.6011	.5580	.5371	.5406	.5673
15	.8162	.6555	.5768	.5369	.5194	.5260	.5561
16	.7935	.6379	.5629	.5261	.5120	.5215	.5547
17	.7804	.6298	.5585	.5246	.5138	.5262	.5626
18	.7763	.6304	.5627	.5317	.5240	.5392	.5787
19	.7803	.6391	.5748	.5467	.5420	.5600	.6022
20	.7918	.6552	.5942	.5689	.5672	.5878	.6329

[a]Derived as a point estimate at each gain contour from the square root function (equation 6.1).

[b]All gain intervals relate to 50 lb. initial body weight.

Table 69. Experiment 6323 - total time[a] in days required to attain the gain specified for gain intervals[b]

Percent protein	Gain intervals (lb.) 0-15 (15)	15-35 (20)	35-55 (20)	55-75 (20)	75-100 (25)	100-125 (25)	125-155 (30)
10	16.77	18.58	16.59	15.44	18.39	18.14	22.14
11	15.41	16.89	14.99	13.91	16.59	16.43	20.20
12	14.31	15.53	13.72	12.72	15.19	15.12	18.74
13	13.43	14.47	12.74	11.81	14.15	14.16	17.69
14	12.75	13.67	12.02	11.16	13.43	13.52	17.02
15	12.24	13.11	11.54	10.74	12.98	13.15	16.68
16	11.90	12.76	11.26	10.52	12.80	13.04	16.64
17	11.71	12.60	11.17	10.49	12.84	13.16	16.88
18	11.64	12.61	11.25	10.63	13.10	13.48	17.36
19	11.70	12.78	11.50	10.93	13.55	14.00	18.07
20	11.88	13.10	11.88	11.38	14.18	14.70	18.99

[a]Calculated from the marginal time predicted by the square root function (equation 6.1).

[b]All gain intervals relate to 50 lb. initial body weight.

Table 70. Experiment 6323 - total time[a] in days required to attain the gain specified at gain contours[b]

Percent protein	Gain contours (lb.)						
	15	35	55	75	100	125	155
10	16.77	35.35	51.94	67.38	85.77	103.91	126.05
11	15.41	32.30	47.29	61.20	77.79	94.22	114.42
12	14.31	29.84	43.56	56.28	71.47	86.59	105.33
13	13.43	27.90	40.64	52.45	66.60	80.76	98.45
14	12.75	26.42	38.44	49.60	63.03	76.55	93.57
15	12.24	25.35	36.89	47.63	60.61	73.76	90.44
16	11.90	24.66	35.92	46.44	59.24	72.28	88.92
17	11.71	24.31	35.48	45.97	58.81	71.97	88.85
18	11.64	24.25	35.50	46.13	59.23	72.71	90.07
19	11.70	24.48	35.98	46.91	60.46	74.46	92.53
20	11.88	24.98	36.86	48.24	62.42	77.12	96.11

[a]Calculated from the marginal time predicted by the square root function (equation 6.1).

[b]All gain contours relate to 50 lb. initial body weight.

Table 71. Experiment 6335 - marginal days[a] per pound of marginal gain over specified gain intervals[b]

Percent protein	Gain intervals (lb.)						
	0-15	15-35	35-55	55-75	75-100	100-125	125-155
10	1.2394	1.0068	.8756	.7923	.7283	.6941	.6804
11	1.1338	.9127	.7901	.7137	.6573	.6298	.6235
12	1.0481	.8381	.7235	.6539	.6048	.5837	.5841
13	.9798	.7805	.6937	.6106	.5684	.5533	.5603
14	.9271	.7380	.6386	.5817	.5462	.5371	.5504
15	.8883	.7089	.6169	.5659	.5369	.5334	.5529
16	.8619	.6921	.6070	.5619	.5391	.5411	.5666
17	.8469	.6863	.6080	.5685	.5517	.5591	.5903
18	.8422	.6906	.6189	.5848	.5739	.5865	.6233
19	.8471	.7041	.6388	.6100	.6049	.6225	.6646
20	.8607	.7262	.6671	.6435	.6439	.6664	.7140

[a]Derived as a point estimate at each gain contour from the square root function (equation 6.3).

[b]All gain intervals relate to 50 lb. initial body weight.

Table 72. Experiment 6335 - total time[a] in days required to attain the gain specified for gain intervals[b]

Percent protein	Gain intervals (lb.) 0-15 (15)	15-35 (20)	35-55 (20)	55-75 (20)	75-100 (25)	100-125 (25)	125-155 (30)
10	18.59	20.14	17.51	15.85	18.21	17.35	20.41
11	17.01	18.25	15.80	14.27	16.43	15.74	18.70
12	15.72	16.76	14.47	13.08	15.12	14.59	17.52
13	14.70	15.61	13.47	12.21	14.21	13.83	16.81
14	13.91	14.76	12.77	11.63	13.66	13.43	16.51
15	13.32	14.18	12.34	11.32	13.42	13.34	16.59
16	12.93	13.84	12.14	11.24	13.48	13.53	17.00
17	12.70	13.73	12.16	11.37	13.79	13.98	17.71
18	12.63	13.81	12.38	11.70	14.35	14.66	18.70
19	12.71	14.08	12.78	12.20	15.12	15.56	19.94
20	12.91	14.52	13.34	12.87	16.10	16.66	21.42

[a]Calculated from the marginal time predicted by the square root function (equation 6.3).

[b]All gain intervals relate to 50 lb. initial body weight.

Table 73. Experiment 6335 - total time[a] in days required to attain the gain specified at gain contours[b]

Percent protein	Gain contours (lb.)						
	15	35	55	75	100	125	155
10	18.59	38.73	56.24	72.09	90.30	107.65	128.06
11	17.01	35.26	51.06	65.33	81.76	97.50	116.20
12	15.72	32.48	46.95	60.03	75.15	89.74	107.26
13	14.70	30.31	43.78	55.99	70.20	84.03	100.84
14	13.91	28.67	41.44	53.07	66.73	80.16	96.67
15	13.32	27.50	39.84	51.16	64.58	77.92	94.51
16	12.93	26.77	38.91	50.15	63.63	77.16	94.16
17	12.70	26.43	38.59	49.96	63.75	77.73	95.44
18	12.63	26.44	38.82	50.52	64.87	79.53	98.23
19	12.71	26.79	39.57	51.77	66.89	82.45	102.39
20	12.91	27.43	40.77	53.64	69.74	86.40	107.82

[a]Calculated from the marginal time predicted by the square root function (equation 6.3).

[b]All gain contours relate to 50 lb. initial body weight.

Table 74. Combined experiments 6323, 6335 -- marginal days[a] per pound of marginal gain over specified gain intervals[b]

Percent protein	Gain intervals (lb.)						
	0-15	15-35	35-55	55-75	75-100	100-125	125-155
10	1.1831	.9705	.8540	.7829	.7321	.7095	.7083
11	1.0844	.8807	.7709	.7052	.6603	.6429	.6474
12	1.0043	.8092	.7056	.6452	.6059	.5934	.6033
13	.9405	.7537	.6561	.6007	.5668	.5591	.5739
14	.8912	.7123	.6206	.5699	.5412	.5381	.5578
15	.8549	.6836	.5975	.5515	.5278	.5291	.5536
16	.8302	.6663	.5856	.5541	.5252	.5308	.5600
17	.8162	.6594	.5839	.5468	.5326	.5423	.5760
18	.8118	.6619	.5916	.5587	.5491	.5628	.6008
19	.8162	.6732	.6078	.5790	.5738	.5914	.6335
20	.8289	.6924	.6318	.6070	.6062	.6276	.6739

[a]Derived as a point estimate at each gain contour from the square root function (equation 6.5).

[b]All gain intervals relate to 50 lb. initial body weight.

Table 75. Combined experiments 6323, 6335 - total time[a] in days required to attain the gain specified for gain intervals[b]

Percent protein	Gain intervals (lb.) 0-15 (15)	15-35 (20)	35-55 (20)	55-75 (20)	75-100 (25)	100-125 (25)	125-155 (30)
10	17.75	19.41	17.08	15.66	18.30	17.74	21.25
11	16.27	17.61	15.42	14.10	16.51	16.07	19.42
12	15.06	16.18	14.11	12.90	15.15	14.84	18.10
13	14.11	15.07	13.12	12.01	14.17	13.98	17.22
14	13.37	14.25	12.41	11.40	13.53	13.45	16.73
15	12.82	13.67	11.95	11.03	13.20	13.23	16.61
16	12.45	13.33	11.71	10.88	13.13	13.27	16.80
17	12.24	13.19	11.68	10.94	13.32	13.56	17.28
18	12.18	13.24	11.83	11.17	13.73	14.07	18.02
19	12.24	13.46	12.16	11.58	14.34	14.79	19.01
20	12.43	13.85	12.64	12.14	15.16	15.69	20.22

[a]Calculated from the marginal time predicted by the square root function (equation 6.5).

[b]All gain intervals relate to 50 lb. initial body weight.

Table 76. Combined experiments 6323, 6335 - total time[a] in days required to attain the gain specified at gain contours[b]

Percent protein	Gain contours (lb.) 15	35	55	75	100	125	155
10	17.75	37.16	54.24	69.90	88.20	105.94	127.19
11	16.27	33.88	49.30	63.40	79.91	95.98	115.40
12	15.06	31.24	45.35	58.25	73.40	88.24	106.34
13	14.11	29.18	42.30	54.31	68.48	82.46	99.68
14	13.37	27.62	40.03	51.43	64.96	78.41	95.14
15	12.82	26.49	38.44	49.47	62.67	75.90	92.51
16	12.45	25.78	37.49	48.37	61.50	74.77	91.57
17	12.24	25.43	37.11	48.05	61.37	74.93	92.21
18	12.18	25.42	37.25	48.42	62.15	76.22	94.24
19	12.24	25.70	37.86	49.44	63.78	78.57	97.58
20	12.43	26.28	38.92	51.06	66.22	81.91	102.13

[a]Calculated from the marginal time predicted by the square root function (equation 6.5).

[b]All gain contours relate to 50 lb. initial body weight.